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BULLETIN OF THE GEOLOGICAL SOCIETY OF AMERICA
VOL. 59, PP. 283-300, 12 FIGS. APRIL 1948

OUR PETROLEUM RESOURCES

BY A. I. LEVORSEN

(Presidential Address of Retiring President of The Geological Society of America)

This evening I would like to talk to you about our petroleum resources. By "our" I mean North American, and by "petroleum" I mean oil and gas occurring naturally. Petroleum is only one of the mineral substances in which the public is vitally concerned as to supply, but it is the one which probably uses the most geology and geologists, and it happens to be the one in which my experience lies.

To begin with, petroleum is important. It is necessary in peace and essential in war. The often repeated statement of Lord Curzon of the British War Cabinet that in War I: "The allies were floated to victory on a flood of oil" applied equally well to World War II when over 60 per cent of the total tonnage—men, munitions, food, and supplies—which was shipped overseas consisted of petroleum products. It is no wonder that a Committee of the United States Senate, after a thorough study and many hearings on the problems of the petroleum industry, made a report containing the following significant statement: "It is now clear that no nation which lacks a sure supply of liquid fuel can hope to maintain a position of leadership among the peoples of the world." This same Committee also stated, in regard to the role American oil played in the recent war, "In the final analysis, the reserves within our borders can more likely than not constitute the citadel of our defense."

Our current use of oil is the greatest in our history—even greater than at any time during the recent war—and much greater than that of any other people. Americans have an annual per capita consumption of 420 gallons as compared with 42 gallons for Great Britain and 14 gallons for all other nations combined. The rate of our use has been accelerating, and all information indicates that it will continue to do so indefinitely. On the other hand, our rate of production already is running so close to capacity that it gives legitimate alarm about our ability to continue to supply adequate amounts of petroleum during the decades ahead. Not only is it necessary to produce enough for our normal expanding peacetime needs, but we must likewise be prepared constantly for any emergency which would again require a sudden expansion of our production. Our future supplies of petroleum are consequently of great national concern.

We often hear the statement made that the discovery of each new oil field means one less in the ultimate finite number of fields. This is correct but rather meaningless. We do our national planning on what we *think* the ultimate quantity is in terms of our needs rather than on any fixed and finite number. Ideas about the future discoveries are constantly changing depending on developments and viewpoints, and varying from extreme pessimism to extreme optimism. For example,

a representative of the State Department recently testifying before a Committee of the United States Senate stated with somewhat of a psychic finality that the reason why we have not found more new oil is: "Because the oil is not there to be found". Far more to the point, it seems to me, would be to reason that because of the recent discovery at the Leduc, or South Edmonton field, in Alberta, for example, we have opened our minds to vast new possibilities in Western Canada. Not one pool less, but rather many pools *more* will result from this one discovery.

The great question facing us now is how long can we continue to replace our annual consumption of petroleum through discoveries of new oil and gas fields? When must we look to other sources—either substitutes or imports from other continents? If we have no more oil to discover, then it is not too soon to start working on some alternate solution. Our needs are great and are constantly increasing. The answer to this problem of adequate supply of petroleum may well become critical to our very existence.

What help can geology give on this problem? Because petroleum is found in the rocks and the earth, and because we, as geologists, represent the science which is concerned with rocks and the earth, we are, whether we wish it or not, faced with a great public responsibility. We are expected to keep the people of North America advised on the prospects of adequate future discoveries of petroleum on this continent. Geology, of all the sciences, offers the key to the evaluation of the ultimate extent of our mineral resources. It is my contention that as geologists, the problem is squarely in our laps, and that our highest social purpose—the finding of new mineral deposits—is being put to a test as never before.

During times of world peace, the petroleum resources of the world are ample to take care of all requirements for generations to come. Petroleum can be moved readily from one continent to another, and the importing of petroleum is a very simple and obvious answer to the lack of it in any part of the world. However, as tensions multiply and international relations become strained, each nation must be prepared to depend entirely on its own resources—that is, those resources which it can protect. In our case, once we on this continent become dependent on a foreign or an ocean-borne supply, not only of petroleum but of every other mineral substance as well, our world position is weakened and our defense and self preservation become proportionately vulnerable.

If we cannot import petroleum with safety to our future, what are the alternatives? The first is to manufacture substitute fuels from our great reserves of coal, oil shales, and tar sands. This seems to offer a solution which is safe, ample in quantity of raw material, and which is technically possible now. The cost is great, however, compared to naturally occurring liquid fuels, and there are many problems which remain to be worked out if such methods are called upon to supply anything more than nominal amounts of petroleum products. But, because there is such a vast amount of hydrocarbon material contained in these deposits, nothing should be left undone which would help make it available for use.

The second alternative is very simple to state but is difficult to achieve. It is to increase oil-field discovery within the continental borders of North America to keep pace with the rising needs. It is this solution that I would like to discuss with you more fully.

If we are to expand our discovery rate, the problem naturally falls into two parts. First, is there enough new oil to be discovered? and second, How is it to be found? The finding of it is readily answered—more drilling. Oil and gas are found in only

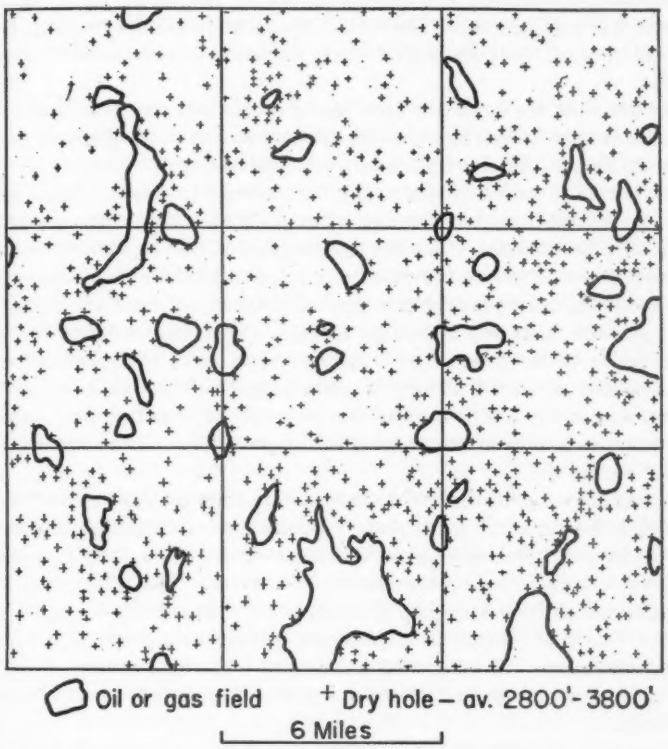

FIGURE 1.—*Drilling density of an area in Oklahoma typical of many counties in the Mid Continent region*

one way, that is by the drilling of wells. The number of dry holes in some of the productive regions of the United States is rather amazing. Figure 1 shows an area of around 320 square miles in Oklahoma which is typical of many counties. The dry holes or salt water wells—each representing a geologic column—average less than a mile apart. One might conclude from this, no wonder they find oil! When we think of the Plains Region of Canada with test wells 50 miles or more apart, the immensity of the drilling program necessary to locate all of the oil fields becomes apparent.

We then come back to the first part, which is the crux of the problem—is there enough oil which remains to be discovered? If there is not, then there is not much need of more drilling. But if there is oil—in terms of our national needs—remain-

ing to be found, then we should be on with the business of locating it. The presently known recoverable oil reserves of 21 billion barrels or more—about 12 times the annual consumption—is merely a working stock. Much of the oil we are using today was unknown 20 years ago, and likewise the oil we will use 20 years hence is in a large part still undiscovered. The really important petroleum resource, then, for the people of North America is that which at present is both undrilled and undiscovered.

A geologist does not physically "see" an oil or gas field any more than a meteorologist, for example, sees a low- or high-pressure area even though both commonly use contour lines to describe the ideas they intend to convey. Both are presenting mental concepts of the conditions as they are thought to exist. Until a discovery well has been drilled, any undiscovered oil or gas field at best exists only as an idea in the mind of the geologist. In a like manner, the basis for any undiscovered petroleum province—a petroleum province being a region in which there are a number of oil and gas pools having related geological conditions—the basis for such an undiscovered province exists only in geologic thought. It is rather sobering to remember that the future of this great natural resource—upon which many national and continental policies are based, industries planned, and defenses built—should rest in the mind and in the imagination of the geologist. Our petroleum resources will not be exhausted until after our imaginative powers have been exhausted. Our job is cut out for us!

There has been a great deal written about petroleum geology—what it is, how it is applied, and what it can accomplish. A crude idea of the philosophy underlying the search for an oil pool, may be stated in three words: "*Find a trap*". Some would add the word, "*First*", to cover the competitive element. As might be expected, such a definition suffers from over-simplification, but it does contain the underlying objective of nearly all petroleum exploration geology and geophysics. Prejudices against fresh water, red sediments, continental beds, high-carbon ratios, lack of source rocks, closeness to the mountains, and lack of sands fade rapidly in the face of a good trap.

It so happens, however, that traps are neither simple nor easy to find. They vary from wholly stratigraphic to wholly structural in character and from Ordovician to Pleistocene in geologic age. They are not the same at depths of 10,000 and 15,000 feet and below several unconformities as they are near the surface; nor are they the same in the centers of the basins as they appear on the outcropping flanks. Seldom is a prospective trap found with more favorable characteristics than unfavorable. As a matter of fact, the final decision as to whether to lease and drill a prospect often depends on extremely tenuous and hazy geologic data, and drilling can be justified only on the basis of experience, imagination, and daring.

Moreover, the average trap is merely the container of one oil field, which in the continental picture is insignificant in terms of the overall requirements. Some oil fields, it is true, are large enough to supply substantial amounts of oil—up to one or two years' needs—but they are rare. Of the 400 to 500 oil, gas, and condensate fields discovered each year, most are relatively small—half a million to several million total barrels—or only enough to take care of the needs of days or even a fraction of

a day. Of the more than 3000 producing oil fields found so far in North America, only slightly more than 100 originally contained more than 100 million barrels of oil, an amount which it should be remembered is only 20 days' consumption. The trend during recent years has been in the direction of more annual discoveries but with smaller size pools, and it is this trend of small discoveries which gives alarm to many persons. To solve the problem effectively, our thinking must be in terms of provinces.

The presently active provinces such as the Gulf Coast, West Texas, the San Joaquin Valley, the Mid Continent states, and the Rocky Mountain region can all be expected to continue to provide new oil and gas fields for many years to come. The prospects for further discovery in these areas are by no means exhausted, but to meet the ever-increasing demands new areas must be added to them.

When in geologic thought we proceed outward from these established areas of production, however, we come into more and more speculative regions which require increasing amounts of geologic imagination to visualize their potentialities in terms of important future supplies. Some examples of these areas or prospective provinces are the Anadarko Basin; the continental shelf; the coastal plains of Mexico; the interior plains of western Canada; Florida and the southeastern states; New Brunswick and other Maritime provinces; the Atlantic Coastal plain; the Great Basin region; the overthrust fault belts and the sediments of Cambrian age. Valid objections, both geologic and economic, can be found to each of these areas which either overbalance the favorable factors or are overbalanced by them depending on who makes the appraisal, for what purpose, and when. There is nothing new in such a statement as every individual prospect, even in the old established provinces, goes through the same sort of reasoning in the normal competitive operation of the petroleum industry. The test well is finally drilled when, in the mind of someone, the favorable factors overbalance the unfavorable. Countless pools have been discovered when the majority, orthodox geologic opinion rated the prospects low, or even negligible and the discovery well had but a small minority support.

The characteristics of provinces parallel those of individual oil fields in many respects, and the single oil or gas pool is often a "hand specimen" of the province insofar as its geologic history is concerned. Experience has shown that every oil field is unique in that it has its own stratigraphic and structural development, and the same uniqueness is true of a province. Therefore, in a new province, we should not expect to duplicate the geologic history found in the proven provinces. Any evaluation of prospective producing regions should depend rather on the objective application of principles to the observed geologic conditions of the area being considered.

Reduced to their simplest terms, the geologic factors which favor a region as a potential petroleum province are: (1) sediments, preferably but not necessarily marine, variable, and unmetamorphosed—generally the more the better; (2) evidences of oil and gas, either from surface seepages or showings in wells; (3) unconformities—also the more the better; and (4) up-dip wedge belts of permeability resulting from any cause. These factors may be termed common denominators of known petroleum provinces, and, while their presence does not assure commercial production in a new region, yet the better and stronger these factors are developed, the better the chances

for such production. Once a petroleum province has been established, there remains only the problem of finding the local traps.

The geologic merit of a prospective region is often tempered by the excessive drilling depths necessary to reach the productive formations. During recent years, the average depth of exploratory drilling has steadily increased, and today wells 12,000 to 15,000 feet in depth are common. The deepest hole to date was drilled last summer in western Oklahoma to a depth of 17,823 feet. It is therefore assumed that test wells as much as 20,000 feet in depth may be considered as practical in the petroleum exploration of the future.

Another important factor which enters into the consideration of a prospective region is its distance from the market. Our petroleum demand is strong enough that it can be expected to reach for supply anywhere on this continent either through pipe lines or ocean transport, provided the supply is large enough to justify the expense. While distance from market is commonly thought of in terms of miles, equally significant are the hurdles which are placed at national boundaries. Our geographic position as a compact continent and the geologic boundaries which determine where our petroleum resources are to be found antedate national boundaries and are far more fundamental to our future welfare than are any man-made rules as to traffic between our countries. It seems to me that we in North America are extremely short-sighted in thinking of ourselves as separate and independent countries when we are so interdependent in terms of all of our natural resources. We on this continent are going to stand or fall together, and there should be no place for trade barriers between our peoples. It is for these reasons that, in appraising our petroleum resources, the prospective areas should be considered throughout all North America, irrespective of the country within which they happen to occur or the distance in miles from the market.

Three of the prospective areas have been selected as typical of the kind and scale of geologic thought and imagination which it seems is necessary to analyze intelligently our undiscovered petroleum resources. They are presented in the discussion which follows. The data used are all taken from geologic articles and publications available to everyone, much of it in the publications of our Geological Society. It is the purpose here to give some indication of the enormous volumes of rocks favorable to petroleum production but which are as yet essentially unexplored. Some of these areas and ideas are highly speculative at this time, but experience has shown over and over again that every producing area, whether an individual field or a great province, was at one time in a similar speculative position.

The areas selected are shown on the North American base map, Figure 2. They are: (1) the overthrust fault belts; (2) the plains regions of western Canada and Alaska and of eastern Mexico and Guatemala; and (3) the wedge out of Lower Cretaceous and Jurassic sediments in the southeastern states.

(1) *Overthrust Fault Belts:* More than 2500 linear miles from 5 to 100 miles wide are shown on the base map in which older rocks are thrust over younger rocks and in which the geology is so complicated as to make it extremely difficult to map and understand. Interpretation of geophysical measurements in these fault areas is generally impossible. The correct knowledge of the geology appears to lie in better

and more accurate surface mapping coupled with careful records of deep wells. Probably of equal importance is the need for geologists to learn more of the nature and mechanics of faulting.

FIGURE 2.—*Reference map of North America showing the three prospective types of areas selected for analysis*

Yet, within these overthrust belts, evidence of petroleum has been found at many places, and several oil fields discovered. One of these belts extends from British Columbia and Alberta south across western Montana and Wyoming and into Utah and Nevada. The Turner Valley pool of Alberta (Fig. 3) is located in it. Another belt is located in the western Ouachita Mountains of Oklahoma and probably extends southwest across Texas. The South Mountain pool (Fig. 4) is one of several examples of oil pools in the Ventura region of California characterized by thrust

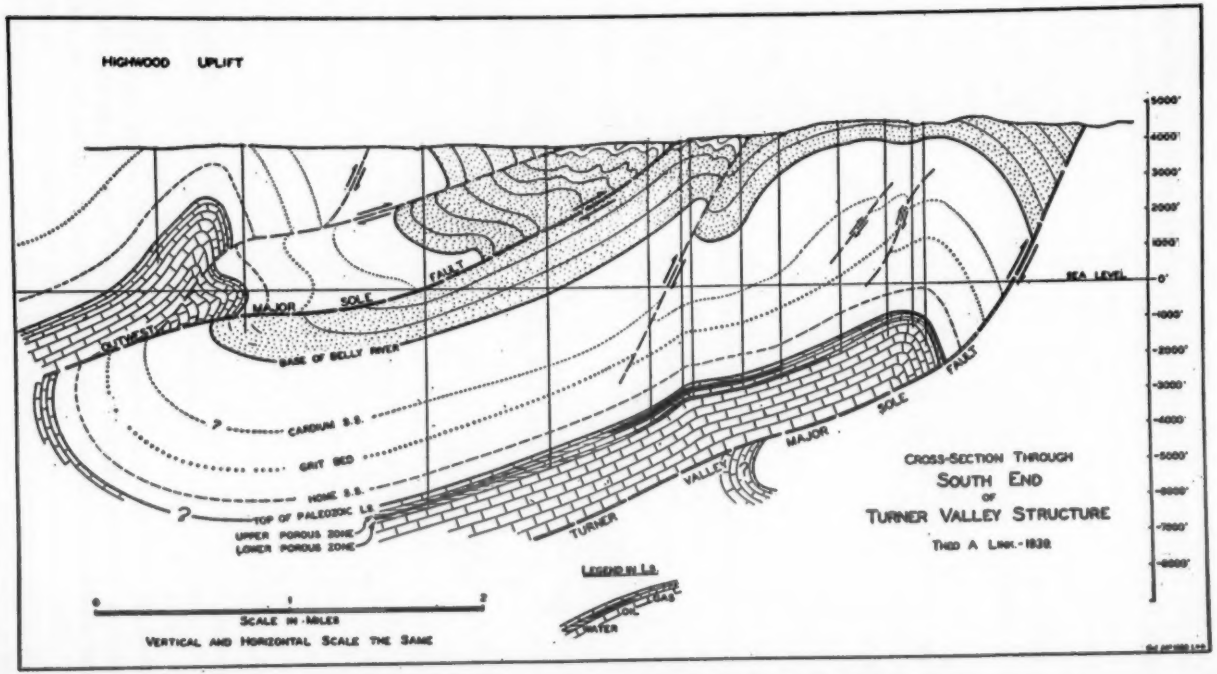

FIGURE 3.—*Section through the Turner Valley field in Alberta, Canada*
After Link.

faulting. The third belt is in the Appalachian Mountains extending from New York into Alabama where it passes under the overlapping Cretaceous and Tertiary rocks. The recently discovered Rose Hill pool (Fig. 5) in Virginia occurs in this belt.

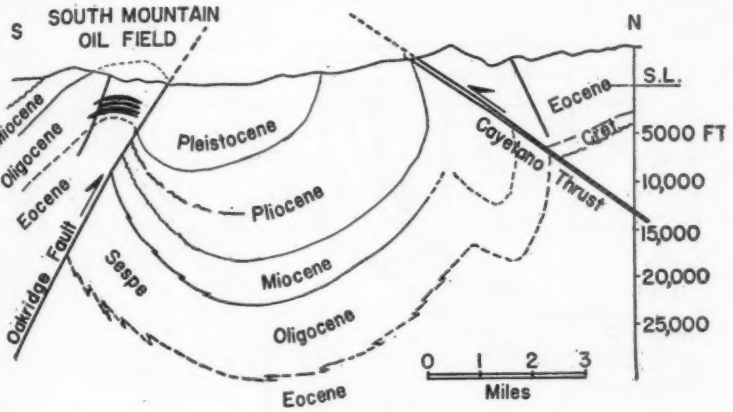

FIGURE 4.—*Section through the South Mountain oil field in Ventura County, California*
After Bailey.

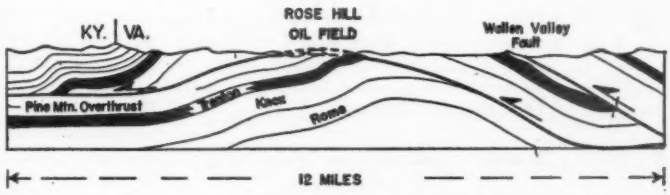

FIGURE 5.—*Section through the Rose Hill oil field in western Virginia*
Production is found in sediments of Trenton (Ordovician) age below the Pine Mountain overthrust fault. After Miller and Fuller.

Apparently thrust faulting and the sort of deformation which occurs in these belts are not detrimental to the occurrence of petroleum.

One factor which makes these belts favorable for petroleum accumulation is the fact that they are generally located over areas in which the sediments increase rapidly in thickness, often thickening at a rate of hundreds of feet to the mile. Wherever sediments thicken, we may expect to find wedge belts of porosity and permeability, a phenomenon common to many proven oil-bearing provinces. Since the belts of expanding sediments antedate the faulting, they thus provide a regional trap before the faulting occurred. In fact, they may have also localized the thrusting over the initial dips which prevailed.

The Choctaw and related overthrust faults in the western part of the Ouachita Mountains of Oklahoma (Fig. 6) deserve special attention as one example of the

scale of trap we may expect to find in these overthrust belts. Here the Ouachita facies of Paleozoic age are thrust northwest out and over the buried Arbuckle rock facies along a front 50–100 miles in length. The surface maps of this part of Oklahoma show the faulted area as separating the Lehigh basin to the northwest

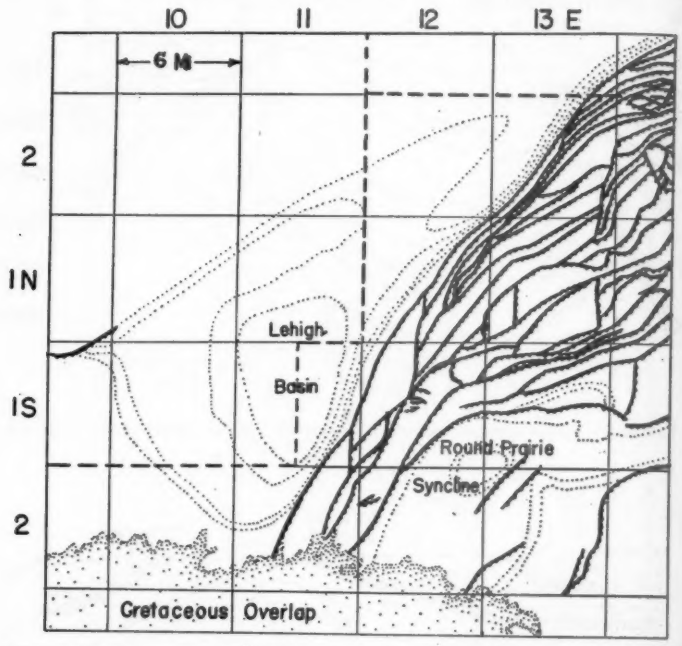

FIGURE 6.—*Details of the overthrust fault belt at the western end of the Ouachita Mountains, Oklahoma* After Hendricks.

from the Prairie Hollow syncline to the southeast, in each of which the rocks are dropped down nearly 2 miles. The map and cross sections recently published by Hendricks of the United States Geological Survey are the basis of the section (Fig. 7). Below the Choctaw overthrust fault, a large anticline is shown in the older Paleozoic formations of the Arbuckle facies, including the Hunton limestone, the Viola limestone, the Simpson sands, and the Arbuckle limestone, all of which are richly productive in the important Oklahoma oil fields 25 to 75 miles to the west and northwest. Moreover, above the area of this fold and within the faulted overthrust rocks are found a large number of oil and gas seepages, asphalt deposits, and other evidences of petroleum. The anticline perhaps differs somewhat from that shown in the section due to the rapid thickening of the Pennsylvanian sediments toward the southeast, but even so there is undoubtedly a fold of some sort in the early rocks at this locality. It is of a size and proportion to justify the belief that, if productive, it will be large—in other words, here is one area possibly containing an unexplored trap a dozen times as large as the Oklahoma City field!

The recent discovery of oil at Rose Hill in Virginia (Fig. 5) located in the overthrust Appalachian region directs attention to a large area of complex geology which has heretofore been greatly discounted because of the high carbon ratios expected. The oil pool is found in dolomites of Trenton age where overridden by early Ordovi-

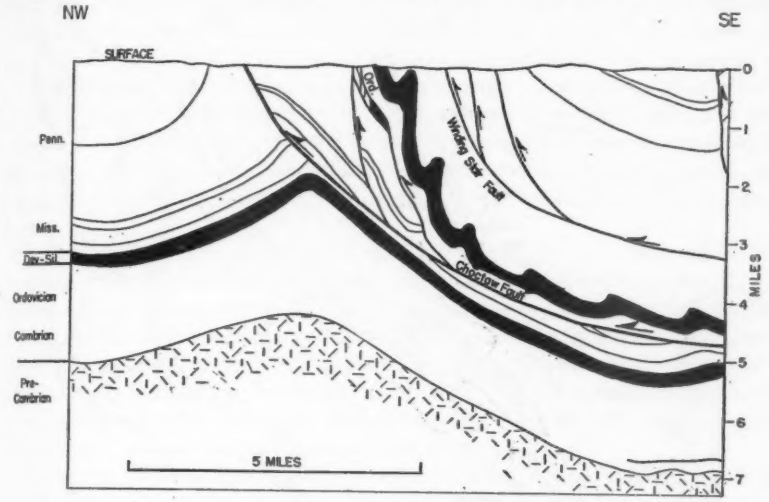

FIGURE 7.—*Section across western end of Ouachita Mountains overthrust fault belt extending from Lehigh Basin to Round Prairie syncline*

After Hendricks.

cian and Cambrian rocks. In addition to the oil at Rose Hill, gas has been found in the overthrust belt at Early and Bristol, both in Virginia. Source rocks consequently have been demonstrated. Folds of all degrees of intensity, coupled with unconformities, facies changes, rapid eastward thickening of all rocks in the geologic column from Cambrian to Pennsylvanian in age, and all sliced with great numbers of low-angle faults assure an almost unlimited number of traps extending from Alabama to Pennsylvania.

An interesting speculation may be made on the basis of the evidence indicated on the geologic map, shown in Figure 8. It is rather evident from this map that the fault belt crosses obliquely an older pattern of folding shown by the anticlinal trends and the regional strike of the rocks. This older lineation is more nearly north and south and passes under the southwest-northeast trend of the later overthrusting. Moreover, the number of faults and their intensity increase from northeast to southwest until the belt passes under the Cretaceous and Tertiary overlap in Alabama. The pattern suggests a sort of pendulum fault movement from AB to AC, the rocks from the east overriding the western rocks a progressively increasing distance from north to south.

The underlying western rocks are known oil and gas producers and may extend far to the east below the soles of the overthrust series. Isopach and paleogeologic maps

offer the means of proving the extent of the overthrusting. Pressure for more oil and gas discovery will provide the incentive for the drilling of the deep holes necessary to test the formations below the faults.

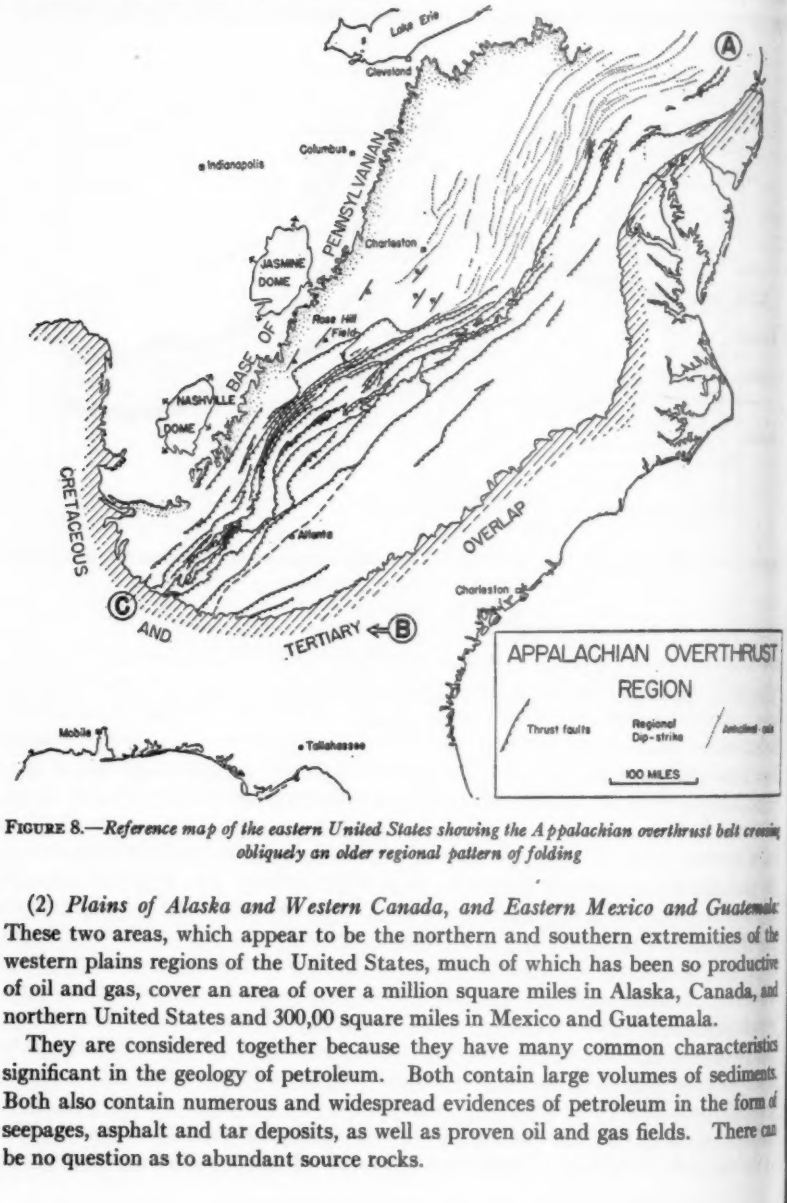

FIGURE 8.—*Reference map of the eastern United States showing the Appalachian overthrust belt crossing obliquely an older regional pattern of folding*

(2) *Plains of Alaska and Western Canada, and Eastern Mexico and Guatemala:* These two areas, which appear to be the northern and southern extremities of the western plains regions of the United States, much of which has been so productive of oil and gas, cover an area of over a million square miles in Alaska, Canada, and northern United States and 300,00 square miles in Mexico and Guatemala.

They are considered together because they have many common characteristics significant in the geology of petroleum. Both contain large volumes of sediments. Both also contain numerous and widespread evidences of petroleum in the form of seepages, asphalt and tar deposits, as well as proven oil and gas fields. There can be no question as to abundant source rocks.

The geologic section in the western Canadian plains contains five regional unconformities, and the Mexican section contains as many or more. One of the important functions of unconformities is to mark the truncation of porous formations below the unconformity. Likewise, the overlapping formations above the plane of the unconformity often contain porous members or lenses. Such stratigraphic phenomena close to unconformities account for a substantial percentage of the world's oil fields. Probably of equal importance to the petroleum geologist is the masking effect of unconformities—they conceal the underlying geology. The presence of an unconformity in the geologic section is notice to the exploration geologist that a new and unknown set of conditions, structural as well as stratigraphic, may be expected to exist below. In many provinces, drilling through unconformities has revealed new and unsuspected deeper formations which caused both geological and geophysical upsets.

In addition to the unconformities, sections of rocks in both areas show numerous changes in facies; lateral variations in porosity, limestone reefs, and interbedded continental and marine sediments. The combination of the unconformities and changes in facies gives to both areas innumerable possibilities for stratigraphic traps of every conceivable variety. Local deformation in an area characterized by such stratigraphic variations need not be strong. Gentle folds, structural terraces, and other minor structures can easily become effective traps for large oil pools especially when combined with lateral changes in porosity and permeability.

The average thickness of sediments in these two areas which might carry petroleum is on the order of 2 miles, which means a total volume of sediments of over 2½ million cubic miles—a truly large volume of prospective material which is today essentially unexplored! It is inconceivable that such a large volume of rocks, in which every prerequisite of a petroleum province is richly developed, should not be the site of hundreds upon hundreds of oil fields yet to be discovered. Deposits such as the Athabaska oil sands of Canada or the Golden Lane and Poza Rica fields in Mexico give a measure of the possible size of some of these undiscovered fields. Not until thousands of additional test wells have been drilled throughout both regions can we say that the exploration of these areas has been completed.

(3) *Southeastern United States:* The dome structure in contours might be called the symbol of the petroleum geologist of the 1920's—it was practically the sole objective in his search for traps. While a dome structure is still as desirable a guide to an oil pool as ever, it is gradually being learned that stratigraphic variations are probably equally as important as folding and faulting in the formation of traps. One of the greatest oil fields in the world, The East Texas field, has a cross section which is symbolic of the changing emphasis (Fig. 9) and which is repeated in many forms in countless oil and gas fields. Whether it is an oil field in the small sand lens in Kansas or Alberta; the porous limestone reefs of West Texas or Mexico; the dolomite grading into limestone in Indiana and Ohio; the rapid lateral change of a sand to shale in California; or the wedges bounded by unconformities as East Texas, the principle is the same—an up-dip wedging out of porosity and permeability in the reservoir rock. This principle applies not only to individual fields, but also to many provinces. Such a province may be looked upon as a large-scale version of the up-

dip wedge of permeability in which the oil and gas are first accumulated in the regional trap and later localized into pools by minor deformations and local stratigraphic variations. Whether the stratigraphic variation is on the scale of either a single pool or a province, it has the advantage of being the earliest trap in the geologic life of the reservoir rock, and consequently having had more time in which to accumu-

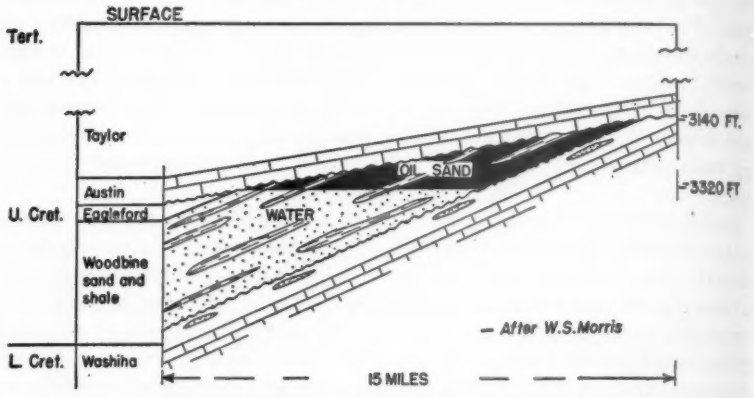

FIGURE 9.—*Generalized west-east cross section of the East Texas oil field*
The wedge shape of the producing formation is repeated in various ways in many oil and gas fields.

late oil and gas. As a consequence, any up-dip wedge edge of permeability in a potentially producing formation is significant.

One ot the largest of these phenomena, which as yet has not been tested, occurs in the southeastern States of Mississippi, Alabama, and Florida where the wedge edge of the Lower Cretaceous and Jurassic rocks crosses first the southwest-plunging Appalachian arch and again the Florida uplift (Fig. 10). These two rock series occur below the Upper Cretaceous in East Texas, southern Arkansas, and northern Louisiana and contain the reservoir rocks of more than 125 oil and gas fields (Fig. 11). This wedge is expanding at a rate of 100 feet per mile down the dip and somewhere in Mississippi and Alabama it crosses the southwestern extension of the Appalachian arch setting up a potential trap area of thousands of square miles. Farther southeast in Florida it crosses the southern extension of the Florida arch where production has already been found in Cretaceous rocks (Fig. 12). Here again there is a potential trap area of thousands of square miles in a group of rocks which have produced fields like Smackover, Rodessa, and Schuler along the same trend. Drilling will be deep, it is true, probably beyond 15,000 feet and even as deep as 20,000 feet. No one can even guess in advance of drilling what structure, stratigraphic sequences, or changes in facies will occur in these rocks, but their past history in Louisiana and Arkansas gives some indication of the possibilities. The scale, both lateral and vertical, is so great that here, again, if production is found, we can expect it to be substantial in terms of national needs.

Ideas on where to drill come from many sources. The farther away from present

FIGURE 10.—*Lower Cretaceous and Jurassic sediments wedge out up-dip across the southwestern-plunging Appalachian Arch and again across the Florida Uplift, thereby forming two large potential trap areas favorable to petroleum accumulation*

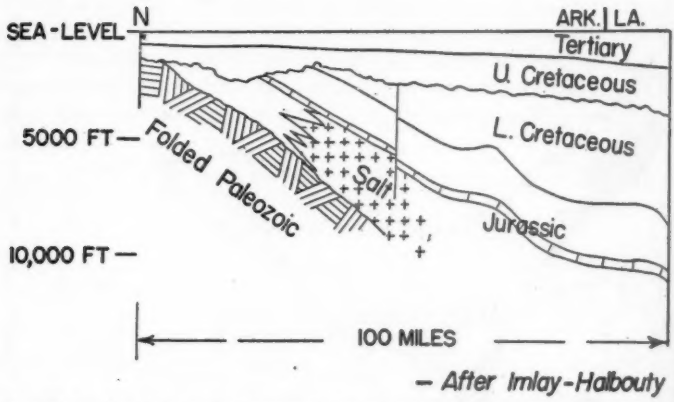

FIGURE 11.—*Wedge-shaped Lower Cretaceous and Jurassic sediments of southern Arkansas and northern Louisiana which provide the regional location for more than 125 oil and gas pools*

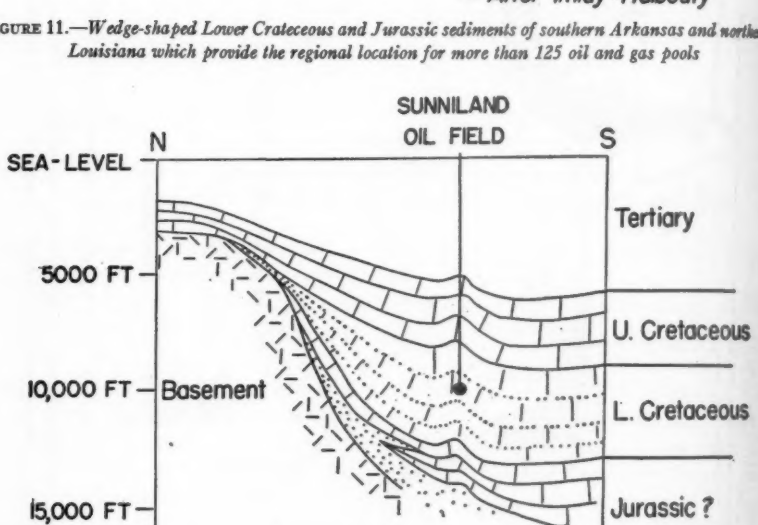

FIGURE 12.—*Same wedge-shaped cross section of Lower Cretaceous and Jurassic sediments (Fig. 11) extends into Florida where it has been found productive at Sunniland*

production we search, the more we depend on sources outside the petroleum industry for our basic data. One such source is the great wealth of geologic data in the publications of our science and particularly in the publications of the Geological Society and the State and National Geological Surveys. These can, with the proper interpretation, point the way to new oil fields and provinces. As a matter of fact, there are probably innumerable oil fields lying buried in our geological libraries—that is, if we knew how to interpret the geology. A recent example of this is the discovery

of oil in the Salinas Valley of California after 50 years of exploration and nearly 90 dry test wells, many of which were drilled on the best geological advice current at that time. The present discovery was the result of drilling a sandy facies which was accurately described by our past Fellow member, Bruce L. Clark, in an article in our Bulletin of 1930. It was covered in two significant sentences:

"The other alternative would be that they (the sediments composing the Monterey deposits) were laid down against the King City fault, which marked the shoreline, and did not extend over the block. If this were true we would expect to find a coarser, more clastic and lenticular series of sediments composing the Monterey along the margin of the King City Block."

I do not know if Mr. Dorrance, who was responsible for the location of the well which the Texas Company drilled, ever saw this statement by Clark, but his reasoning in making the location was the same. This idea lay in libraries all over the world for 17 years without a taker!

Adding up all of the prospective areas which have been both mentioned and described, we find enormous volumes of rocks which have geological conditions more or less favorable to the occurrence of petroleum, yet which have had relatively little exploration. The reasonable conclusion is that they contain proportionately large petroleum deposits, and that our exploration job is still far from complete. It is extremely doubtful if the geology of any of these areas will ultimately prove to be exactly as it is now envisioned. As long, however, as favorable geologic factors remain, there is reason for drilling and, if drilling, then hope for additional discovery. Our responsibility is to maintain the best scientific guidance for the drilling.

Petroleum geology is geology applied to the problems of the petroleum industry which in turn is devoted to the service of man. The industry is prepared to spend unlimited amounts of money and effort to maintain discovery, and the foundation of discovery is geology. There is scarcely a phase of the science of geology that does not find an application. What began on the part of the oil industry as a half-hearted use of surface structural mapping has now developed into great geological organizations, equipped with enormous research facilities and utilizing a wide variety of principles of geology, physics, chemistry, and engineering. The broad front on which petroleum geology has developed is significant, for it adds powerful support to fundamental research—that phase of geology to which we in the Geological Society are especially committed.

Finally, I like the idea expressed by Doctor Conant,* President of Harvard University, when, after defining a "scholar" as: "including all those who are endeavoring to be original thinkers in any field of learning", he states that: "a scholar's activities should have relevance to the immediate future of our civilization." The problem of an adequate supply of mineral resources—not only petroleum but other mineral substances as well—is surely a part of the immediate future of our civilization. You and I, who may be called scholars attempting to do original thinking in the field of geology, might well heed his admonition. Such thinking is, indeed, high-level geology. It is a field in which the scholars of The Geological Society of America have played a vital part in the past and are needed more than ever in the future.

*James B. Conant: *The American Community of Scholars*, Address delivered at the Inauguration of Arthur Holly Compton as Chancellor of Washington University, St. Louis, Mo., February 22, 1946.

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STRATIGRAPHICAL PALEONTOLOGY

BY RAYMOND C. MOORE

(Address as Retiring President of the Paleontological Society)

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INTRODUCTION

The subject of Stratigraphical Paleontology, on which I have chosen to address you, is one that touches virtually every branch of geological science, for conclusions derived from the nature and distribution of fossil plants and animals are the indispensible foundation of geochronology.

I propose to review some of the primary features belonging to fossils as markers of geologic time, as criteria for correlation of sedimentary strata, and as guides to accurate interpretation of sedimentary environments. It is profitable for us periodically to scrutinize the nature of our accumulated knowledge, to inquire as to soundness of our basic concepts, to appraise the adequacy of our work methods, and to formulate an outlook on needs for future research. Naturally, most of what I shall say does not express ideas originated by me, but I venture to pronounce some conclusions of my own which I hope you will judge to be worthy of attention.

The survey which I undertake is necessarily selective and somewhat cursory. To begin with, how shall we define stratigraphical paleontology? What is its scope? G. Arthur Cooper has remarked that stratigraphical paleontology is a hybrid mixture of stratigraphy and paleontology, which, being neither fish nor fowl, has no good standing as an independent science or subscience. This is not a fair characterization. Of course, stratigraphy embraces much that is independent of paleontology, as in study of unfossiliferous rocks like most pre-Cambrian formations, evaporites, and various continental deposits. On the other hand, paleontology cannot exist without its stratigraphic setting, and stratigraphy would be almost wholly sterile without paleontology. In my view, stratigraphical paleontology is synonymous with paleontology itself, viewed with the eyes of a geologist, whereas so-called systematic paleontology comprises a purely biological approach, without reference to geology except for arrangement of fossils in order of time succession. Stratigraphical paleontology is not merely an application or adaptation of a segment of biological science to help establish correlations of strata and confirm arrangement of rocks in a geologic column. It is rather the study from all angles of ancient organisms of the earth in their geological setting

As for the status of paleontology in relation to geology, on the one hand, and to zoology and botany, on the other, I take friendly issue with J. Brookes Knight, who held in his presidential address to the Paleontological Society last year that paleontology and the training of paleontologists should be removed from beneath the geological mantle and housed with the biological sciences. Though we grant that paleozoology and paleobotany are integral parts of zoology and botany, and that adequate preparation for researches on fossil faunas and floras demands thorough training of students in biological science, it is nevertheless true that paleontology is indissolubly a part of geologic science. This side of geology utilizes zoology or botany just as other aspects of geology depend on chemistry and physics. The study of the chang-

ing nature of the earth's past organic assemblages, their distribution and varied environmental setting, as determined from evidence found in rocks, is much more closely akin in interest, objectives, and techniques to geology than to zoology or botany. Stratigraphical paleontology is thus a biologic branch of geology, and its place in university curricula seems as clearly to belong in the department of geology as do chemical and physical branches of geology.

EVIDENCE FURNISHED BY A SINGLE FOSSIL

First, let us review the nature of evidence furnished by an isolated individual fossil —say, a well-preserved fern leaf or a clam shell—found in a given sedimentary deposit. For the moment we shall neglect the fact that where one fossil occurs, commonly there are many. Among things determinable with varying precision from study of this single fossil are: (1) the structural or morphologic characters of the organism, which provide basis for comparison with all other known forms of life and for judgment of its relative biologic advancement; (2) the physical environment in which the organism lived and in which the fossil-bearing sedimentary deposit was formed; and (3) the geologic placement of the organic remains with reference to older (underlying) and younger (overlying) deposits. Chief things not determinable from the specimen before us, assuming that no other fossils are brought into view, are: (1) paleontological correlation with any other beds, and (2) geological antiquity of the fossil. Observation of occurrence of the fossil-bearing rock in the local stratigraphic succession can merely establish that the fossil is older or younger than associated sedimentary deposits. In general view, if paleontological basis for interrelating rock sections in various parts of the world were lacking, we could not even start to guess the position of our fossil in a general time scale. These points are elementary and obvious.

Now for a moment let us contemplate the occurrence of a single species of organism —not a single specimen—as found distributed in a bed or beds of rock in a region. Such a fossil species may be an extremely reliable, and therefore highly valuable, means of tracing and correlating equivalent strata. It may also be diagnostic of depositional environment. The precision of correlation depends on the restriction of the fossil to corresponding beds in the vertical succession, and the extent to which correlation may be carried follows on geographic distribution of the fossils. The paleontological markers may be viewed as distinctive lithologic constituents which are exactly analogous to bright pink pebbles confined to certain layers. There is no guaranty, however, that in a different area of sedimentation identical sorts of "pink pebbles" correspond exactly in age to those of the region previously considered. Thus, the local abundance of any kind of fossil in a given layer or zone has practical usefulness in stratigraphy, such fossils being classifiable as distinctive lithologic components of the strata concerned, but occurrence of the same species in some other area may be stratigraphically dissimilar to that in the first area.

Excellent examples of distribution of a fossil like that just noted are found in many places. Thus, a relatively long-ranging species of the brachiopod *Crurithyris* is found to be persistent in several thin zones in Pennsylvanian and Lower Permian rocks

of Kansas (Fig. 1). In conjunction with other features, each such zone can be identified and traced by means of the occurrence of abundant *Crurithyris* in it. The fossil is a distinctive lithologic constituent having restricted stratigraphic placement. Accurate paleoecological interpretation of the occurrence of these fossils depends on many things.

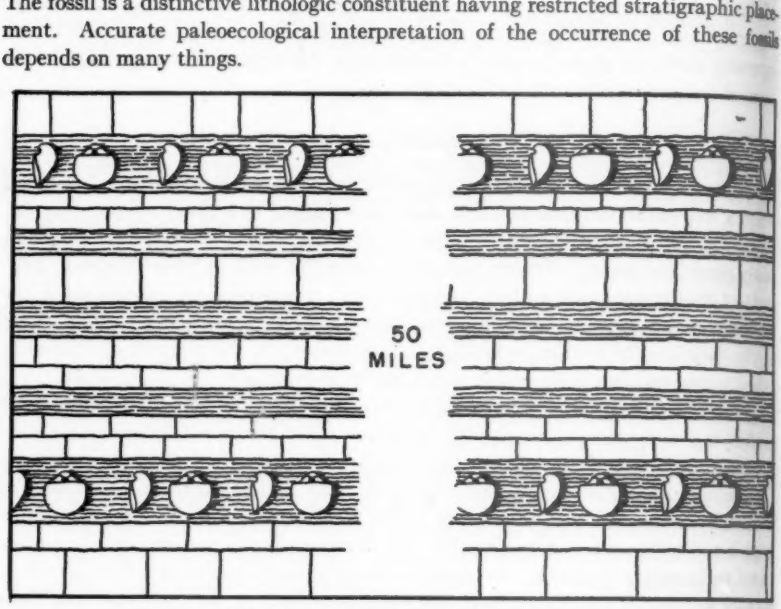


FIGURE 1.—*Occurrence of a single species of fossil* (Crurithyris planoconvexa) *in Lower Permian rocks of Kansas*

Abundance of this fossil in two thin shale deposits, in conjunction with absence or rarity in other beds, as diagrammatically represented, serves as an aid in correlation. The fossils are distinctive lithologic constituents of the shales.

EVIDENCE FURNISHED BY A SINGLE FOSSIL ASSEMBLAGE

Suppose we consider next a natural assemblage of several sorts of fossils found together in a sedimentary deposit of small thickness at a given place, excluding all other fossils from notice. Such an assemblage, assuming that it contains no worn, secondarily deposited fossils, represents a contemporaneous or nearly contemporaneous group of organisms which may be termed a faunule, if composed of animals, or a florule, if composed of plants. Consideration of this faunule or florule shows that our capabilities and limitations in deriving significant conclusions are pretty much like those found in attempting to interpret an artificially isolated single specimen or species.

Let us assume that our selected assemblage of fossils in beds at a certain place is found to match with essential exactness collections made at several other places. Does this similarity or identity of characters pertaining to an assemblage of organic remains furnish superior basis for stratigraphic correlation and indication of geologic age, as compared with evidence given by similar occurrence of a single species? The answer is affirmative as regards correlation, because the assemblage comprises a

multiple record, and this is best suited to reflect variations of any sort. As indicator of geologic age, however, a single assemblage of fossils, whether known from a small area or widely distributed, has no value at all, if neither antecedent nor subsequent groups of fossil are discovered. Furthermore, identical fossil assemblages obtained from different places are not necessarily contemporaneous, for they may owe their identity to similarity of sedimentary facies.

Ecologic analysis of the elements in a fossil assemblage of the sort discussed may be approached by comparison with most closely similar modern natural assemblages of plants or animals, and the evidence furnished by the fossil organisms generally is highly useful to the stratigrapher and student of sedimentation in picturing the conditions under which the fossil-bearing strata were made. Among marine organic groups, one may recognize assemblages of bottom-dwelling invertebrates, some growing throughout post-larval life in fixed position, attached to foreign objects or embedded in sediment of the sea floor, and others of crawling or burrowing habit, or able to move short distances above the sea bottom. These groups may be classified according to their several environmental adaptations, as inhabitants of the surf-agitated near-shore, shallow-water offshore, moderately deep still-water offshore, brackish water of estuaries, warm clear shallow water of reefs, and many others. Temperature, salinity, depth, water movement, and nature of the sea bottom are factors having important influence on these marine organisms. Then come questions as to whether an assemblage being studied is indigenous to the place where the fossils are found (a so-called biocoenose, comprising a community of organisms that lived together where they are found) or whether the organic remains have been carried wholly or in part from elsewhere (a so-called thanatocoenose, comprising a group of organisms brought together after death). Perhaps free-swimming or floating organisms, such as fishes, pelagic Foraminifera, and the like, are admixed with bottom-dwellers.

Inasmuch as buried hard parts of plants or animals by no means exclude remains introduced from adjoining or distant areas, a paleontologist must not be surprised when occasionally he finds fossils derived from older rocks associated with those representing organisms that are contemporaneous with the sediments inclosing them. Such reworked fossils are not always differentiated by obvious signs of wear or other readily recognized marks.

Continental deposits containing bones of vertebrates, shells of fresh-water or terrestrial mollusks, or leaves of land plants may represent a wide variety of environments above sea level, and evidence furnished by the organic remains, skillfully interpreted, has utmost importance in constructing the geologic record.

SIGNIFICANCE OF MULTIPLE FOSSIL ASSEMBLAGES

GENERAL DISCUSSION

Actually, the paleontological record consists of innumerable successive and laterally modified or intergrading fossil assemblages. Many of these are extraordinarily rich in variety of forms and number of individuals. Some may be collected and prepared very easily. The form and structure of the almost perfectly preserved hard parts

may be studied in minute detail. Other groups of fossils are the opposite in character, consisting of only a few forms which are inadequately represented by individual specimens; preservation is poor; the collection and preparation of material for study is extremely difficult. Worse than this are wholly fragmentary, virtually indecipherable organic remains and traces of more or less indeterminate nature. Many rock units have yielded no identifiable fossils of any sort. Between the extremes are all possible intermediate types of occurrence of fossils. Let us review certain aspects of these multiple fossil assemblages, good, bad, and indifferent.

An introductory comment bearing on the completeness and quality of source data for work of the stratigraphical paleontologist seems pertinent. I suggest that generally far too little time and labor are expended on the task of searching for good fossils, finding the best collecting localities, making adequate collections, and caring for collected specimens properly. The average geologist engaged in an areal or economic study in which features of the stratigraphic column, including age determination of rock divisions and reliable interpretation of paleogeographic relationships, must be studied, thinks that he has performed well the paleontological amenities if he gathers a very few fossils, perhaps fragmentary, throws them casually into a sack without wrapping, and eventually puts them into someone's hands for identification. Average to good stratigraphers and even many who call themselves paleontologists do not know how to collect fossils, as is proved by the fact that in quantity and quality any collections of fossils made by them are almost invariably very inadequate. The result is that our knowledge of the fossil content of sedimentary deposits in many regions is woefully incomplete.

The use of special techniques in collecting and preparing fossils, wherever suitable, is likely to yield large dividends. Examples are the etching of silicified Permian fossils from western Texas, and Ordovician trilobites, bryozoans, and other invertebrates from Virginia, which has supplied a large quantity of superlative paleontological material. Knowledge of the content of numerous successive faunal assemblages is being extentanded greatly.

STRATIGRAPHIC PLACEMENT

The primary control for establishing the true significance of fossil assemblages in rock strata of the earth is their stratigraphic placement. When this is clearly determined, the nature of the several assemblages assumes meaning and importance. Unfortunately, some paleontologists, chiefly early investigators of fossil vertebrates, have paid rather scant attention to the geologic roots of their science. Although they are aware that arrangement of fossil faunas and floras in the stratigraphic succession governs all sorts of deductions relating to prehistoric organisms, they give very inadequate information on the geologic setting of their fossils. It should be emphasized once and for all that, if stratigraphic and geographic placement of a fossil is lacking, it has little scientific value.

RELATION TO GEOLOGIC TIME

The Englishman, William Smith, "Father of stratigraphic geology," is credited with first distinguishing and making practical use of constant differences in the nature

of fossil assemblages found in successive rock strata as means of identifying and tracing various layers. His work, about 150 years ago, on Jurassic sedimentary deposits of southern England was the beginning of investigations on the occurrence of fossil groups distributed throughout the geologic column, first in Europe, and subsequently in all other continents. With minor variations, that are interpretable as reflecting regional change, the nature of successive faunal and floral assemblages has been found to match one another closely, even in many widely separated areas. Local absence of certain organic groups can be understood to mean nondeposition of rocks belonging to the concerned part of the rock column, or prevalence of conditions unsuited to burial and preservation of organisms, or removal of fossil-bearing strata, which once were present, or it may signify geographic variation in the distribution of the concerned organic group. The empirically determined sequence of fossil faunas and floras in different parts of the world has been fitted together with varying definiteness so as to form a connected and interrelated record. Average rates of organic change in response to evolutionary tendencies can be expressed. This change seems to be much accelerated in some classes of organisms as compared with others, and assuredly it is true that the pace of alteration in form and structure runs far from constant during the time span from advent to disappearance of many biologic assemblages. Fossils furnish reliable evidence of relative geologic age, although they offer no means for measuring absolute geologic age.

It is pertinent to ask how exactly equivalence in age may be indicated by the same fossil or group of fossils found in different places. Some workers (Ulrich, 1911, p. 295) have pointed out the extreme rapidity of geographic migration, even of bottom-dwelling invertebrates of the sea, as compared with rates of sedimentary accumulation. This means that, wherever conditions favorable for migration of an organism are offered, the spread of that form of life may occur with what amounts to geologic instantaneity.

It does not follow that all known occurrences of a given fossil—for example, the distinctive Devonian brachiopod *Stringocephalus burtini*, which ranges from northwestern Europe across Asia and North America as far southeastward as Manitoba—are to be reckoned as contemporaneous within very narrow geologic time limits. An organism that originates in some one region may exist there during an indefinitely protracted time span before conditions favor widespread migration; or it may persist in some part of the world well after the time of its disappearance elsewhere. Witness, the startling capture of a supposedly long-extinct type of Cretaceous coelacanth fish (*Latimeria*) in deep waters off the southeastern African coast a few years ago.

Regional variation in recorded stratigraphic range is increasingly likely, the broader and simpler the organic entity concerned; that is, the vertical distribution of genera commonly shows greater regional disparity than that of species, and the range of an unspecialized form, like *Lingula*, is much greater than that of a highly modified brachiopod, like *Leptodus*. A faunal or floral assemblage containing several distinctive, somewhat narrowly defined species and occurring in two or more places ordinarily can be adjudged to be closely contemporaneous throughout the known area of its distribution. Naturally, the greater the geographic spread of such an assemblage, the larger is the room for some difference in age of different parts. Possibly excepting

correlations based on occurrence of short-lived free-floating or swimming organisms of the sea, such as graptolites and some cephalopods, or rapidly migrating land animals and plants, most intercontinental correlations of fossil species or assemblages cannot be accepted as indicating precise contemporaneity.

The requirements for more accurate and detailed correlation of fossil-bearing deposits in all parts of the world, and for derivation of a more accurately integrated geologic time scale, expressed in organic terms are: (1) vastly more thorough collecting of fossils both by zones and localities; (2) great enlargement of the body of carefully worked descriptive paleontology; (3) more exact and complete data on stratigraphic distribution of described forms; (4) greater understanding and taking account of facies relationships; and (5) analytical syntheses of several sorts, including comparative tables, maps, and sections, serving to interpret the basic data.

The first of these requirements can be met only by increased manpower, working skillfully and perserveringly with adequate funds for exploration. The labor by several generations of scientific collectors is needed.

The second demand calls for a very thorough knowledge of the morphology and systematic relationships of the organisms studied, with development of penetrating judgment of features having most importance in evolutionary differentiation; specialists on biologically defined segments of the faunas and also, to some extent, on major parts of the geologic column must be available for these tasks.

Integration of these studies, utilizing materials called for in the third, fourth, and fifth requirements stated above, doubtless can be effected best by well-trained stratigraphical paleontologists who undertake to specialize on relatively restricted parts of the geologic column, such as the Devonian or Jurassic deposits and organisms of the world.

As illustration of needs, I suggest that if a comprehensive survey should be undertaken, making appraisal of all published studies dealing with North American fossils, it would probably indicate that less than 2 per cent of the separately named stratigraphic units of the continent could be classified as explored paleontologically so as to define in anything like reasonably adequate manner the character and distribution of their organic remains. It is true that much work has been done, but critical examination of published studies calls attention to the magnitude of deficiencies. I do not intend to imply that we lack highly competent paleontologists, past and present, or that we encounter serious inadequacies in all but a few contributions. Rather, I express judgment that the number of able workers has been and is far too small for accomplishment of needed paleontological research at a pace corresponding to advancement in other geological fields. The scope of many studies is too limited, and delineation of many morphologic, stratigraphic, and ecologic features is too lacking in definiteness and completeness.

RELATION OF ORGANISMS TO ENVIRONMENT

Every plant and animal is adapted in varying degree to its surroundings. This sensitivity of organisms is so prevalent that virtually every fossil may be classed as a facies fossil. As used by many geologists, the term facies is understood to embrace the composite features of any geologic setting expressed in characters of rocks. There

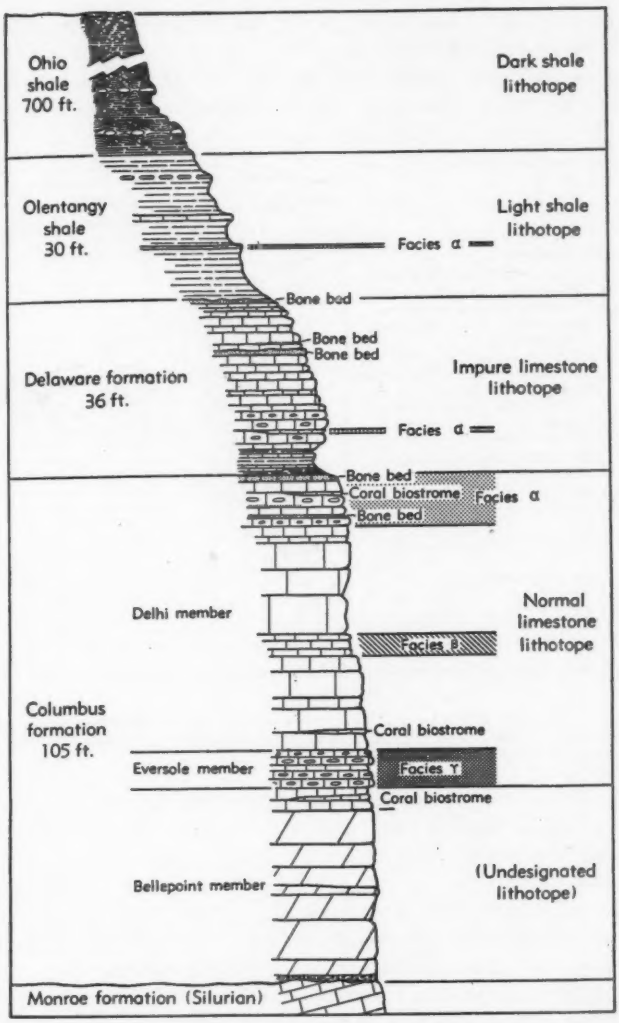


FIGURE 2.—*Lithotopes and facies in Devonian strata of central Ohio*

(Modified from J. W. Wells). The term lithotope is intended to incorporate all physical and organic attributes of a sedimentary deposit having significance as records of environment. The term facies is employed to designate recognized variants or aspects of a defined lithotope or specified stratigraphic unit, such as a formation or member. As treated by Wells, the coral biostromes, bone beds, and strata referred to Facies α, β, and γ are differentiated from the designated lithotopes.

are cogent grounds, it seems to me, for differentiating terminology employed to express characters of any single sedimentary deposit in terms of environment from that designed to express variations in character from place to place within a specified

stratigraphic unit. J. W. Wells (1947, p. 119) has proposed the term *lithotope*, meaning rock environment, to designate in collective manner all attributes of a deposit bearing on its conditions of origin (Fig. 2). The term *facies* is best employed in its root meaning to express a particular variant or aspect among two or more types of deposits belonging to a designated stratigraphic unit or category.

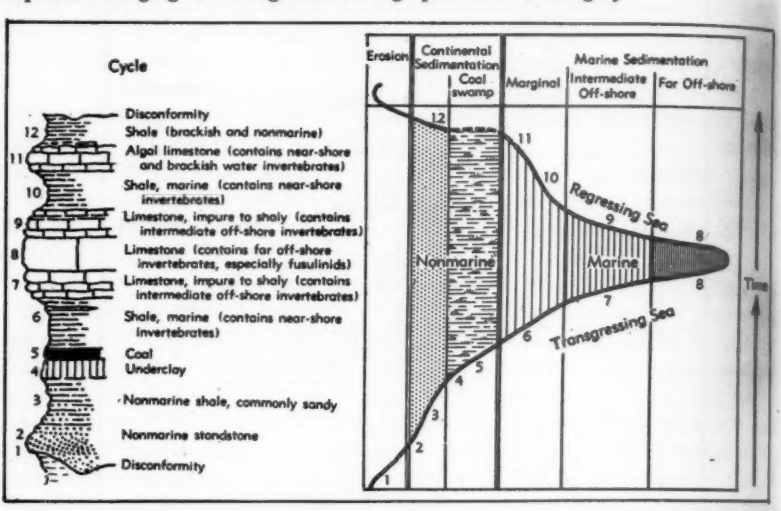


FIGURE 3.—*Abrupt changes of environmental features represented by successive deposits belonging to a Pennsylvanian cyclothem in Kansas*

The organic remains found in different strata (Nos. 2–12 in section at left) chiefly reflect environment, and paleontological differences are almost wholly ascribable to this influence. The diagram at right interprets the setting of the numbered rock units in terms of indicated advance and retreat of marine waters.

Obvious differentiation of organisms according to environment is that which separates animals and plants of the land surface and the air from organisms of the sea. Within each of these realms there are myriads of special environments. It is important to inquire as to the manner in which environment controls the nature of fossil assemblages and affects their distribution. Variation is clearly demonstrated in many places by deposits of different character that are proved to be contemporaneous by their laterally intergrading or interfingering relationships, and these contemporaneous deposits may lack almost any common elements. A horizontal shift of environments, such as occurs commonly in marine transgression or regression, or in the spread of fluviatile deposition over an area of former lakes and swamps, introduces abrupt change of fossil assemblages in vertical sequence (Fig. 3). The age difference of the superposed layers is trivial, but the organic change is profound.

Recognition of the significance of paleoecology in stratigraphical paleontology calls attention to the necessity of making comparisons solely between assemblages belonging to like environments. Rocks of like facies having identical organic assemblages may be accepted as equivalent in age, unless qualifying features dictate otherwise. Within a given deposit of uniform lithologic character having considerable thickness,

change of organic assemblages that proceeds with lapse of time may make distinction of the lower, intermediate, and upper assemblages easily possible. Despite persistence of nearly identical environment, animals or plants suited to this habitat may exhibit significant change, some may disappear either by extinction or migration,

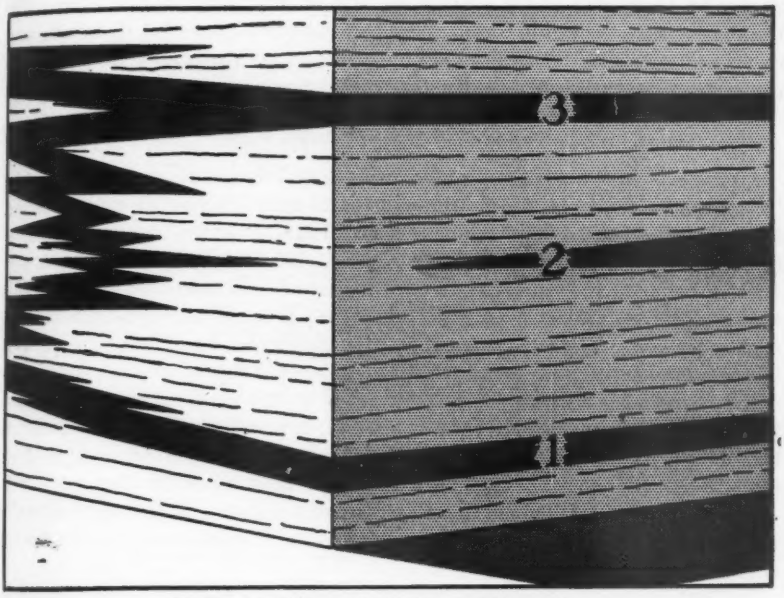


FIGURE 4.—*Diagram showing "recurrent faunas"*

The fossil-bearing strata are represented by sections in two planes that intersect approximately at right angles. In the plane at right, the fauna of the black shale (1) recurs with virtually no change at higher positions (2, 3); in the plane at left, the persistence of black shale deposition in an irregularly shifting belt is indicated.

indigenous new species may be developed, and immigrants from other areas may appear. In general, any stratigraphically constant variation in an element of the assemblage desirably calls for classificatory differentiation as a specific or subspecific paleontological unit.

The progression of faunal or floral change in a persistent sedimentary environment has no necessary relation to that of others. It may be rapid in one and slow in another. Relations of each to others of contemporaneous origin can be determined only where they are physically adjoined or happen to contain fossils in common, or where they are framed below and above by strata that are respectively equivalent. The phenomenon of so-called recurrent faunas or floras merly represents oscillatory repetition in the sequence of deposits at a given place (Fig. 4) of the lithotope or facies to which the animal or plant groups are adapted. The recurrent assemblage is constituted of the descendants of the earlier populations, which, during absence from the area under study, survived in places where suitable environment persisted. Close paleontological comparison of the antecedent and recurrent faunas commonly shows

distinctions of the same sort as are found in faunas from the lower and upper parts of a thick deposit of uniform lithologic character.

Lateral shift of a given sedimentary environment with lapse of geologic time, in such manner that rocks of similar lithology obliquely transgress time lines, is accompanied by persistence of the appropriate organic assemblage of the facies. This readily may lead to error in correlation if true relationships are not discerned and if minor paleontological distinctions are unrecognized. Classification and nomenclature of deposits in many places wholly fails to take cognizance of facies relationships.

CONCEPTS OF PALEONTOLOGIC ZONES

Efforts have been made along various lines to divide rocks of the geologic column into paleontologic zones, which are presumed to embrace rocks of equivalent age. Some are defined on a continent-wide or even an intercontinental basis, and these may be measurably independent of the lithology of contained strata. Inasmuch as they are based on observed characters and distribution of fossil assemblages, they cannot transgress major lithotope boundaries, particularly those separating marine and nonmarine deposits. The recognition of zones, accompanied by effort to extend them laterally as widely as possible, and study of the interrelation of different sets of paleontologic zones are essential parts of the task of integrating the stratigraphic record in different parts of the world. As yet, however, no standard scheme of zonation has been developed that may be applied very widely or to other than certain parts of the column—notably the richly fossiliferous Mesozoic rocks of western Europe.

Partition of the stratigraphic succession into various types of chronogeologic units—that is, rocks formed during a specified geologic time span—defined by occurrence of fossils include the following:

(1) Divisions called *faunizones* (Fig. 5), based on the vertical range of selected assemblages of fossil animals, and *florizones*, based on occurrence of groups of fossil plants, are defined with contiguous boundaries. According to usage, faunizones and florizones may be defined to include less than the known total range of constituent organisms in the selected assemblage; in this sense the zones comprise designated successions of beds that are characterized by prominence of the fossil assemblages. Inasmuch as components of the fossil faunas and floras generally overlap, selection of the boundaries is arbitrary except where the line of separation coincides with a stratigraphic hiatus. The name of a characteristic animal or plant, as the case may be, generally is employed for designation of the faunizone or florizone, and it is noteworthy that the stratigraphic boundaries of such zones commonly do not coincide with known limits of range of the organism chosen as name-giver to the zone. The widely recognized zones in the European Jurassic succession, which largely follows classification of Oppel (Arkell, 1933, p. 18, 28; Muller, 1941, table 2, fol. p. 1432), are good examples of faunizones. These are mostly named from species of ammonites. Commonly in writing, faunizones and florizones are simply termed zones.

(2) Divisions called *biozones* (Fig. 5) are defined by the stratigraphic span of the absolute lower and upper limits of some selected organism—plant or animal, genus or species—occurrence of which is presumed to be sufficiently abundant and widespread to have value as a chronogeologic indicator. The names of such biozones naturally

are derived from the selected marker organism. Zones of this sort are likely to offlap or overlap one another, except perhaps along lines of stratigraphic discontinuity, for in a conformable rock sequence it is unlikely that the upper boundary of one biozone should coincide with the lower limit of a neighboring one. The concept of biozones

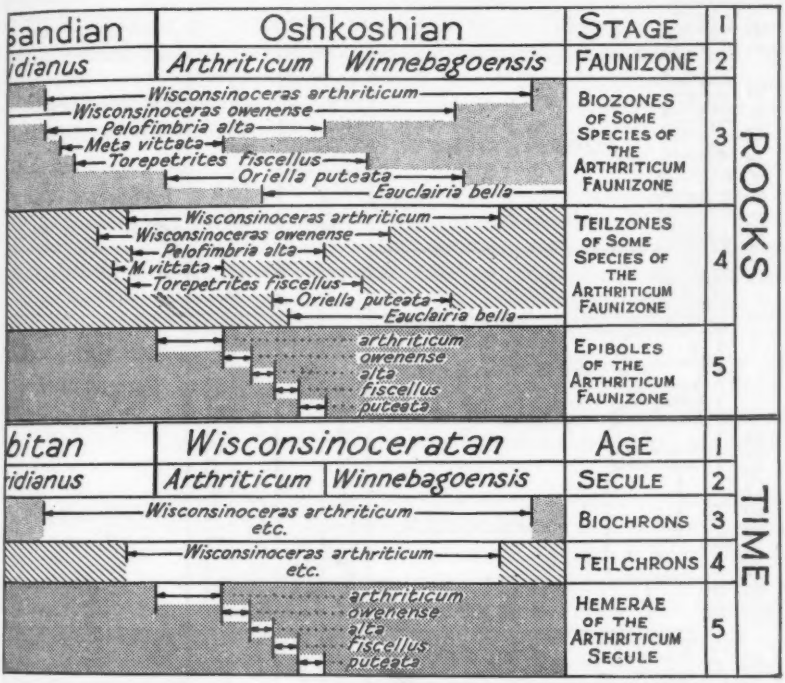


FIGURE 5.—*Diagram showing relations of time-rock and time divisions defined mainly or wholly on fossil invertebrates*

The divisions of varying rank are designated by fictitious stratigraphic and paleontologic names, which are nonexistent in literature. They are intended to illustrate concepts in zonation and corresponding segmentation of geologic time.

seems to have little practical use, inasmuch as the total range of the guide fossil controls definition; the observed vertical distribution of most fossil organisms varies from place to place, and total range always is difficult to determine with certainty.

(3) Divisions called *teilzones* (Figs. 5, 6) have been proposed to include strata characterized by the occurrence of selected guide fossils in any given area. They are defined in terms of a chosen genus or species, rather than an assemblage of fossils. The stratigraphic span of teilzones is not determined by relative abundance of the guide fossil, and, depending on local differences in range, it may vary from place to place. The boundaries of teilzones based on different organisms have no necessary relation to one another, for these limits may coincide, overlap, or offlap. Obviously, new finds that extend the known local range of the guide fossil of a teilzone modify definition of the teilzone.

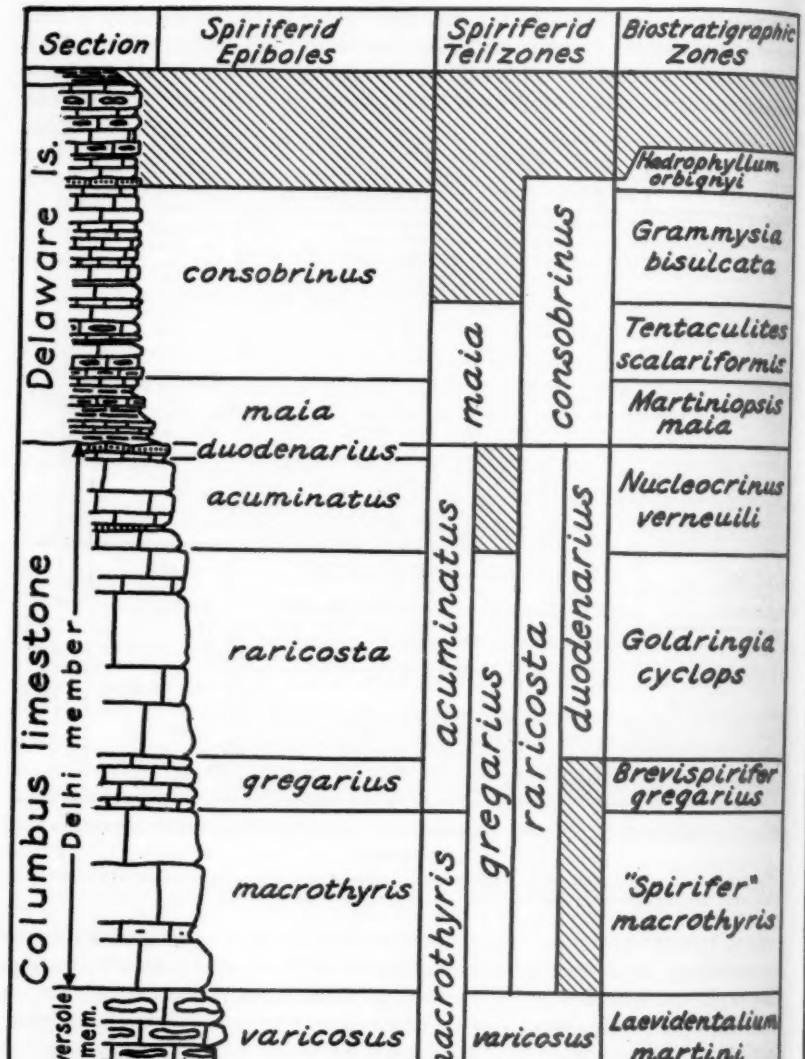


FIGURE 6.—*Paleontological zonation of Devonian rocks in central Ohio*

(Modified from J. W. Wells). The zonation in terms of spiriferid epiboles (improperly called hemerae by Wells) is shown to differ, except for the *varicosus* epibole, from spiriferid teilzones, which represent the total known range of the designated species in the central Ohio Devonian section. The so-called biostratigraphic zones, indicated at right, are in part epiboles; some may be teilzones or, insofar as determinable by me, they may be arbitrary extensions of teilzones.

(4) Divisions called *epiboles* (Figs. 5, 6) are defined to contain strata characterized by the special prominence or presumed importance of a selected genus or species of fossils. They constitute the part of a biozone that normally represents the acme in occurrence of the marker fossil. The boundaries of epiboles are arbitrarily selected, and thus it is readily possible to divide local rock successions into a set of contiguous paleontological zones of this type which do not overlap. Subdivisions of faunizones which have been made in Jurassic sections of various parts of Europe are mostly epiboles named after species of ammonites (Arkell, 1933, p. 38). Frequently, these paleontologically defined units are simply termed subzones. Difficulty in extending such zonal divisions beyond the limits of a natural depositional province are obvious.

Classification of parts of the geologic column on the basis of characteristic genera or species belonging to different classes of animals or plants, as found in literature, varyingly follows the pattern of biozones, teilzones, and epiboles. The actual stratigraphic ranges of the guide forms in various examples, such as Pennsylvanian and Permian fusulinid zones defined by Dunbar (1940) and Thompson (1948), late Paleozoic cephalopod zones recognized by Bisat (1928; 1936) and Schmidt (1928), and echinoid zones in Mesozoic strata of Western Europe defined by Lambert and Thiéry (1909–1925), may equal, exceed, or be less than the assigned stratigraphic limits of the zone. It may also be noted that zonation of the same strata in terms of different classes of organisms commonly do not correspond, because evolutionary development of these classes—frequently characteristic of different sedimentary facies—are not the same.

Not only faunal zonation but also conclusions as to age assignment of a given sequence of deposits occasionally differ according to studies by different investigators working with various segments of organic assemblages. An example is furnished by paleontological determinations derived from studies of Pacific Coast Tertiary deposits (Weaver *et al.*, 1944), wherein conclusions by students of the Foraminifera differ radically from those of investigators of various megafossil groups. This discrepancy signifies incomplete knowledge, for it is inconceivable that different elements of the same organic assemblages should tell a conflicting story as to geologic age.

Time terms corresponding to different categories of paleontological zones are indicated in Figure 5. None are commonly used in historical geology, however.

CONCEPTS OF STAGE AND SUBSTAGE

A time-rock stratigraphic unit next below series in rank has come to be known generally as stage, and main divisions of a stage may be designated as substages. Some workers treat substage as synonymous with zone and prefer the latter designation.

There is lack of agreement in the method of defining both stage and substage or zone, particularly as regards delineation of boundaries.

It is understood that physical criteria of many sorts, as indicated by rock composition and texture, mineral associations, insoluble residues, electrical and radioactive characters, and structural relations, have bearing on differentiation of lesser time-rock units in any region, and these rank with organic criteria. The chief difference in viewpoints relates to the basic pattern of classification. According to concepts of

most stratigraphers, the limits of any two adjacent time-rock units in a series theoretically coincide; there is neither offlap nor overlap of the boundaries. The total number of stages in a series, or of substages in a stage, depends on the fineness of stratigraphic partition, and if all are added together they precisely equal the span of the time-rock unit that is next higher in rank.

A different scheme recognizes time-rock units classed as stages or substages that do not have contiguous boundaries necessarily. The limits of these units may offlap or overlap one another in variable manner, and according to different chosen criteria there may be a dozen sets of classifications applied to the same beds. Thus, if so-called stages are defined in a given area on grounds of the observed distribution of (a) foraminifers, (b) brachiopods, (c) corals, (d) crinoids, (e) bryozoans, (f) cephalopods, (g) land plants, or (h) dominant lithologic features, there may be eight sets of differing time-rock units, in each of which the respective individual units may adjoin, overlap, or offlap one another. Such procedure makes stage (and substage) virtually or precisely synonymous with faunizone, florizone, or other types of zones previously discussed, and I am strongly of the opinion that such units should not be defined as stages or substages.

SIGNIFICANCE OF AREAL DISTRIBUTION OF FOSSILS

GENERAL STATEMENT

Stratigraphical paleontology is concerned with the nature and distribution of fossil organisms in space—that is, their geographic spread—quite as much as their occurrence in time, as shown by presence in different parts of the geologic column.

Every organism having characters that permit its differentiation from others must have origin at some given place on the earth's surface, and descendants may be expected to spread laterally insofar as favorable conditions of physical setting, supply of food, and relative freedom from enemies or strong competitors permit. The population developed in the general region of origin is properly termed indigenous, or autocthonous; segments of the population that migrate into distant new territory are exogenous or allocthonous elements of the population of these areas. No sharp line can be drawn between these fractions. It follows that the makeup of any organic assemblage living together at a given place is made up of (a) indigenous elements derived from antecedent individuals that had occupied the area for a long or a short time, (b) and recent immigrants from some adjoining territory. Changes in a population can originate by extinction of species, disappearance of species by emigration, introduction of indigenous new species by evolutionary change, and immigration of new forms. Considering the whole, it is evident that there must be a continuously varying life pattern both in space and time. Identical or closely related organisms living in different areas may give rise to descendants of generally similar but slightly divergent characters. Given time and isolation from each other, all these differences tend to become accentuated.

CONCEPT OF FAUNAL AND FLORAL PROVINCES

Organisms of modern lands and seas show regional variation that is plainly related to geographic influences and an expression of them. We may expect that similar

conditions of differentiation prevailed during past earth history, although by no means does it follow that the modern pattern of geographic organic realms is mirrored by earlier geologic epochs.

Any region characterized by broad similarity of faunal or floral components in its life assemblage, and differentiated in definite manner from other areas, may be recognized as a biologic province. The boundaries of such provinces among marine organisms commonly coincide with land barriers, but they may be marked by barriers of temperature or oceanic depths. Provinces on land may be outlined by sea margins, mountain ranges, desert barriers, or marked changes of temperature. Cosmopolitan faunas and floras denote the breaking down of provincial boundaries and development of widespread general uniformity of life conditions.

Life variations within a province are subordinate to those that distinguish the province from others, and mainly they reflect differences in environment. Recognition and correlation of such variations of fossil assemblages call for notice of lateral gradation or interfingering of strata that contain dissimilar but contemporaneous organic remains.

Recognition of age equivalence of sedimentary deposits belonging to different biologic provinces, both broadly and in detail, is generally a difficult problem. Satisfactory solution sometimes is not attainable, because we are dealing with independently evolving groups of relationships that may have no common denominator. Occurrence of equivalent guide horizons in the different regions occurring below and above the dissimilar provincial fossil-bearing sequences may give control for general age assignment, and this is likely to find corroboration in broad affinities and similarity in the evolutionary stage of development of the respective groups of organisms. Varyingly detailed exact correlation between biologic provinces is furnished by local and occasional breaking down of the provincial barriers which permits temporary invasion of organisms of one into the other. Numerous examples of such relationships are found in the stratigraphic record of different parts of the world, as in the Culm goiniatite-bearing shaly-siliceous province in Lower Carboniferous deposits of Europe and equivalent coralline-brachiopod strata laid down in geographically distinct areas.

FRAGMENTARY FOSSIL REMAINS

The systematic paleozoologist or paleobotanist is inclined to be little interested in fossils that lack reasonably definite indication of the form and structure of the complete organism to which they belong. It must be granted that isolated teeth of fishes, reptiles, or mammals, dissociated segments of crinoid stems, and fragments belonging to wholly unknown organisms, such as conodonts, are highly inadequate as materials for construction of an even approximate characterization of entire organisms. Nevertheless, many such fragmentary fossil remains are so widespread and abundant in many rock layers, and so distinctive in individual markings, that patently they have value in stratigraphical paleontology. Fairly extensive work has been done on some of these groups of fragmentary remains, notably the conodonts, but other very promising categories, such as echinoderm fragments, are virtually untouched.

GUIDE FOSSILS

Comment on the subject of guide fossils is in order here. The term guide fossil is commonly understood to mean any type of organic remains that is sufficiently widespread and abundant in a more or less restricted thickness of beds to have value as an

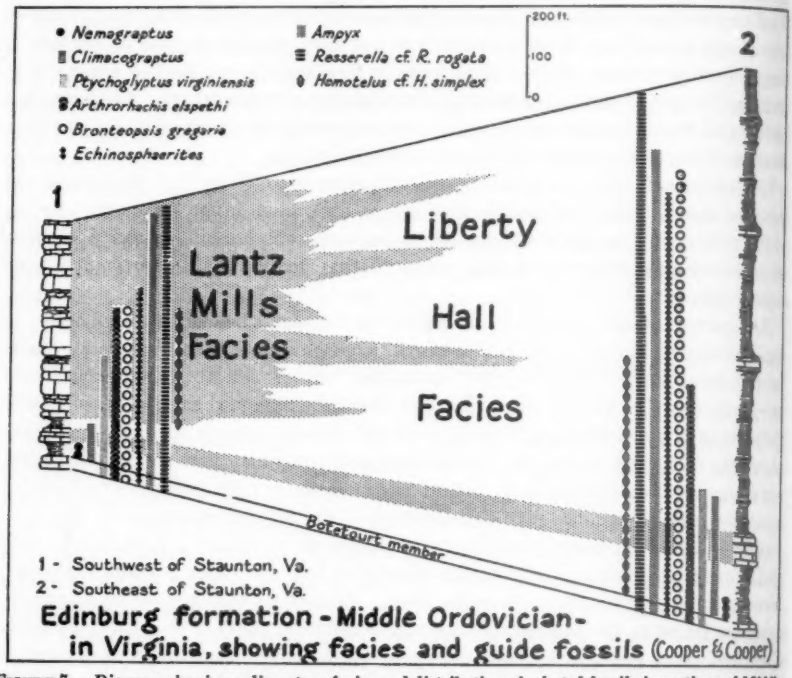


FIGURE 7.—*Diagram showing sedimentary facies and distribution of selected fossils in sections of Middle Ordovician rocks of southwestern Virginia*

indicator of geologic horizon and age. In varying degree, innumerable kinds of fossils have attributes that qualify them for inclusion among guide fossils. Caution must be exercised, however, and the complexly variable conditions that affect distribution of most types of animals and plants must be remembered, if error in conclusions as to age equivalence of beds containing the presumed guide fossils is to be avoided. Particularly important is recognition of facies variations as a factor controlling occurrence of many forms of life. Examples of gross misconceptions of the stratigraphic relations and geologic age of Ordovician formations of the Central Appalachians region have been pointed out recently by Cooper and Prouty (1943) and Cooper and Cooper (1946). These errors came mostly from reliance on assumed constant stratigraphic placement of lithologic character of deposits and occurrence of such fossils as *Cryptophragmus* and *Maclurites*. When note is taken of the entire faunal assemblages and when their relation to varying types of sedimentary environment is observed, a radically changed outlook on stratigraphy and historical geology is provided (Fig. 7).

REQUIREMENTS FOR ADVANCE IN STRATIGRAPHICAL PALEONTOLOGY

GENERAL APPRAISAL

The century and a half during which investigations bearings on stratigraphical paleontology have been prosecuted in many parts of the world is a period in which enormous progress has been made. Despite many major uncertainties, firm ground has been reached for understanding broad relationships of the rock succession on all the continents. Multitudes of detail have been gathered in many regions, and it is important not to overlook additions to knowledge of the nature and distribution of fossils in buried deposits, coming especially from work done by American paleontologists on fossils from deep borings.

With all this in mind, it is salutary to undertake appraisal of the tasks ahead. Despite advancements just noted, I am led to judge that present-day workers in stratigraphical paleontology may rank themselves not far beyond very early investigators such as Deshayes, Sowerby, Phillips, Quenstedt, D'Orbigny, Oppel, and many other pioneers in development of paleontological science. This estimate rests less on consideration of the little-known fossil-bearing rocks in many parts of the world than on needed studies of fossil assemblages already investigated to some extent. In comprehensive view, work on the stratigraphical paleontology of North America may be said to be only well started. Critical re-examination of most earlier work is required.

I shall enumerate six main needs of stratigraphical paleontology, as I view them.

INCREASE OF TRAINED MANPOWER

Undoubtedly there is great need today both for a larger number and better scientific preparation of investigators in paleontological fields. In spite of economic applications of paleontological study, numerous qualified specialists in this line of work were withdrawn during the war for other sorts of duty. The war has ended, but several of these paleontologists are not yet at work in paleontology. There is prospect, moreover, that some may not return at all.

In viewing manpower needs, I am not inclined to lay stress on economic paleontology, but rather to emphasize the fundamental place occupied by paleontology in advancing our understanding of the sedimentary rocks. Lack of progress during many years on many paleontological fronts, and the volume of investigative work that needs to be done, signify a call for new talent in this branch of geology much more than sufficient to maintain a *status quo*. There is need also for more thorough training and better comprehension of work to be done than many of us present-day paleontologists possessed on leaving school.

Currently, there is a serious shortage of competent teachers of stratigraphy and paleontology, as has been made evident by unsatisfied calls from many universities during the past couple of years. Moreover, the outlook is not very good for early betterment of this shortage. A survey of 23 leading graduate schools which I made recently has yielded information that only 8 doctorates in paleontology are listed in 1947, about 15 in 1948, and perhaps 12 in 1949. A majority of these young workers are primarily engaged in stratigraphical studies that embrace some paleontological

research; very few are mainly engaged in invertebrate paleontology. The figures given do not take account of doctorates in paleobotany and vertebrate paleontology.

IMPROVEMENT IN PALEONTOLOGICAL AND STRATIGRAPHICAL DISCRIMINATION

We have need for greatest possible competence and thoroughness in paleontological researches, accompanied by precision in recording and interpreting the stratigraphical setting of studied fossils.

Some published works, both early and recent, measure up well according to all standards; they constitute solid foundations for subsequent building even though a few stones must be reshaped. These are architecturally sound structures which are located on the right street and appropriately laid out on the correct lot; in other words, good paleontology is accurately placed in stratigraphic relationships.

An unfortunately large part of paleontological literature, on the other hand, is deficient—some of it very sadly so—in describing, illustrating, classifying, and interpreting essential characters of fossils, and data on the occurrence of studied specimens are indefinite.

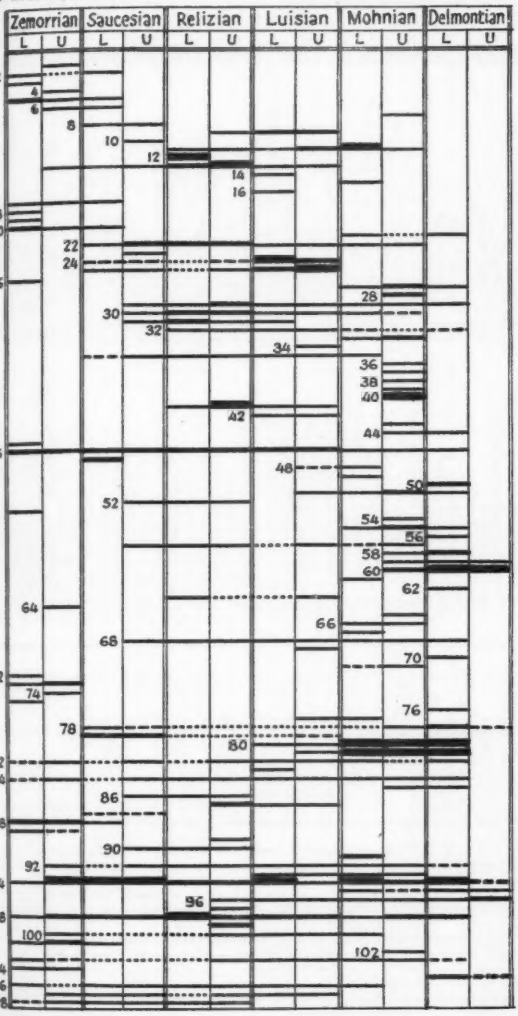
These remarks are not to be interpreted by anyone as assumption by me of better-than-thou attainments. I simply observe that real advancement in stratigraphical paleontology demands utmost penetration of all aspects of biological science applied to the study of fossils, combined with painstaking attention to the observation, recording, and interpreting of stratigraphical relationships of the fossil assemblages studied. In support of this assertion, and as examples of work that measures up well in my opinion, I cite studies by Dorothy Hill on corals, G. Arthur Cooper on brachiopods, N. D. Newell on clams, L. W. Stephenson on Cretaceous mollusks, and I might add numerous others. I am much impressed by demonstrations touching all parts of the paleontological world from Cambrian to Pleistocene, in which discernment of previously unobserved morphologic distinctions, or ecologic relationships, or both, furnishes correlations and understanding of stratigraphical placement. In my judgment, a sound and virtually indispensable test for the recognition of species and subspecies among fossils is found in correlated constants of morphology and stratigraphical occurrence.

Thus, we require greatest possible competence and thoroughness of biological and stratigraphical approach on the part of paleontological workers.

AVAILABILITY OF MORE AND BETTER FOSSILS

The best possible material for paleontological investigations, accompanied by precise stratigraphic and geographic data, seems clearly to be a factor important for accelerating progress in research. Increased readiness on the part of museums, universities, and geological surveys to loan available collections for study by competent workers should contribute to this end. But there must be also considerable enlargement and improvement in the gathering of new materials for paleontological studies.

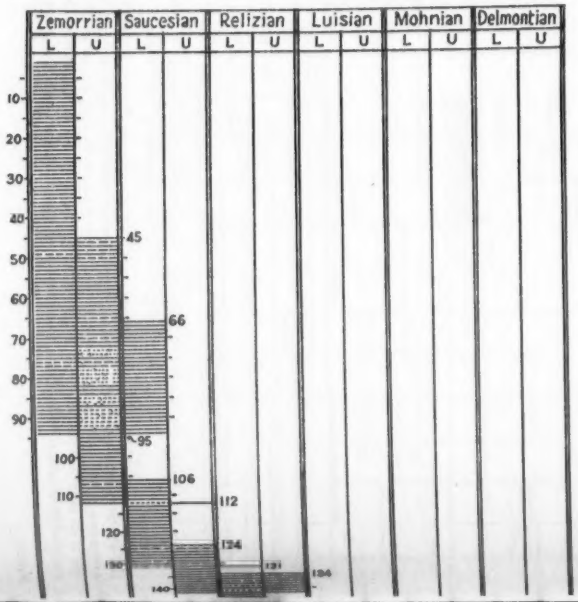
Encouragement of amateur enthusiasts in collecting fossils seems generally to be undesirable, since specimens valuable for paleontological research are more likely to be lost to science than gained. The average amateur has little appreciation of the scientific importance of fossils that he may find, is often careless in handling them,



1—*Ammobaculites strathearnensis*
2—*Ammodiscus* cf. *incertus*
3—*Amphimorphina* (?) cf. *californica* (1)
4—*Angulogerina occidentalis* (95)
5—*Anomalina californiensis* (66)
6—*A. plabrata* (106)
7—*A. hughesi* (230)
8—*A.* cf. *patella* (124)
9—*A. salinasensis* (160)
10—*A.* (?) sp.
11—*Baggina californica*
12—*B. cancriformis* (143)
13—*B. robusta* (352)
14—*B. robusta globosa* (170)
15—*B. subinaequalis* (200)
16—*Bathysiphon arenacea*
17—*B. filiformis* (?) (317)
18—*B. sanctaecrucis*
19—"*Bathysiphon* (?) sp."
20—"*Bathysiphon* sp. (?)"
21—*Bathysiphon* (?) sp.
22—*Bolivina advena* (360)
23—*B.* aff. *advena* (132)
24—*B. advena ornata* (299)
25—*B. advena striatella* (300)
26—*B.* aff. *alazanensis* (2)
27—*B. barbarana* (220)
28—*B. bramlettei* (231)
29—*B. brevior* (366)
30—*B. californica* (364)
31—*B. conica* (306)
32—*B. cuneiformis* (371)
33—*B. decurtata* (214)
34—*B. dumlapi* (183)
35—*B. floridana* (359)
36—*B. girardensis* (232)
37—*B. goudkoffi* (233)
38—*B. granti* (234)
39—*B. hootsi* (235)
40—*B. hughesi* (236)
41—*B. imbricata* (313)
42—*B. imbricata inflata* (174)
43—*B.* cf. *interjuncta* (237)
44—*B. malagaensis* (247)
45—*B.* cf. *mantaensis* (3)
46—*B. marginata* (340)
47—*B. marginata adelaidana* (113)
48—*B. marginata gracillima* (192)
49—*B. modeloensis* (201)
50—*B. obliqua* (260)
51—*B. parva* (325)
52—*B. perrini* (134)
53—*B. pisciformis* (4)
54—*B.* aff. *plicata* (238)
55—*B. pseudospissa* (221)
56—*B. rankini* (261)
57—*B. salinasensis* (365)
58—*B. seminuda* (248)
59—*B. seminuda foraminata* (254)
60—*B. sinuata* (255)
61—*B. sinuata alisoensis* (202)
62—"*Bolivina* sp (?)"
63—*Bolivina* sp.
64—*B.* sp. (?)
65—*B. subadvena spissa* (239)
66—*B. subhughesi* (215)
67—*B. ticensis* (203)
68—*B. tumida* (367)
69—*B. tumida cuneata* (184)
70—*B. vaughani* (262)
71—*B. woodringi* (216)
72—*B. ynezana* (5)
73—*Bulimina carnerosensis* (45)
74—*B. carnerosensis mahoneyi* (96)
75—*B. corrugata* (6)
76—*B. delreyensis* (263)
77—*B. galliheri* (193)
78—*B. inflata* (362)
79—*B. inflata alligata* (301)
80—*B. montereyana* (321)
81—*B. montereyana delmonteensis* (326)
82—*B. ovata* (341)
83—*B.* cf. *ovata*
84—*B. ovula* (342)
85—*B. ovula pedroana*
86—*B. pseudoaffinis* (135)
87—*B. pseudotorta* (161)
88—*B. pyrula* (125)
89—*B. rinconensis* (67)
90—*B.* cf. *socialis* (46)
91—*B.* (?) sp.
92—*B. subcalva* (136)
93—*B. wigerinaformis* (204)
94—*Buliminella brevior* (357)
95—*B. californica* (319)
96—*B.* aff. *californica* (185)
97—*B. curta* (346)
98—*B. dubia* (331)
99—*B. elegantissima* (374)
100—*B. henryana* (149)
101—*B. semihispida* (240)
102—*B. subfusiformis* (343)
103—*Cancris baggi* (150)
104—*C. brongniartii*
105—*C. sagra* (68)
106—*Cassidulina barbarana* (241)
107—*C. crassa* (344)
108—*C. crassipunctata* (47)

FIGURE 8.—*Range chart showing known stratigraphic occurrences of Foraminifera, alphabetically arranged, in Miocene deposits of California*

(After R. M. Kleinpell). This figure presents data on less than one third of the species recorded in Kleinpell's (1938, p. 137–151) table, but the alphabetical arrangement of entries follows the original publication. Like all tables constructed in this manner, the result is a "scattergram," which poorly serves the ends of stratigraphical paleontology because much study of the table is required to distinguish the most significant features of faunal distribution. (Dashed lines indicate uncertain identification; dotted lines indicate absence of record between older and younger occurrences reported; thickness of lines indicates relative abundance. Numbers in parentheses following names of species indicate placement in Figure 9.)



1—*Amphimorphina* (?) cf. *californica* (3)
2—*Bolivina* aff. *alazanensis* (26)
3—*B.* cf. *mantaensis* (45)
4—*B. pisciformis* (53)
5—*B. yneziana* (72)
6—*Bulimina corrugata* (75)
7—*Cibicides dohertyi*
8—*C. haidingeri*
9—*C. hodgei*
10—*C.* aff. *perlucidus*
11—*C. pseudoungerianus evolutus*
12—*Clavulina bramlettei*
13—*C. communis pallida*
14—*C. cyclostomata*
15—*Dentalina* aff. *mucronata*
16—*D. pioneerensis*
17—*Ellipsonodosaria recta*
18—*E.* (?) cf. *verneuili*
19—*Epistomina ramonensis*
20—*Eponides condoni*
21—*E. frizzelli*
22—*Haplophragmoides advenus* (?)
23—*Lagena strumosa*
24—*Nodosaria* cf. *boffalorae*
25—*N. hamilli*
26—*N. holserica*
27—*N. pyrula*
28—*N. pyrula semirugosa*
29—*N.* cf. *soluta*
30—*Nonion affinis*
31—*N. yneziana*
32—*Pseudoglandulina gallowayi*
33—*Pullenia bulloides*
34—*P. octoloba*
35—*Pulvinulinella* cf. *culter*
36—*Robulus* cf. *clericii*
37—*R. coloratus*
38—*R.* sp.
39—*Sigmoilina tenuis*
40—*Textularia* cf. *gramen*
41—*T. shivelyi*
42—*Uvigerina gallowayi*
43—*U. gesteri*
44—*Valvulineria casitasensis subcasitasensis*
45—*Bulimina carnerosensis* (73)
46—*B.* cf. *socialis* (90)
47—*Cassidulina crassipunctata* (108)
48—*Dentalina spinosa*
49—*Guttulina hughesi*
50—*G.* cf. *irregularis*
51—*Lagena clavata*
52—*Nodosaria estorffi*
53—*Nonion* cf. *labradoricus*
54—*Planulina cushmani*
55—*Plectofrondicularia barbati*
56—*P. vaughani*
57—*Robulus barbati*
58—*R.* cf. *calcar*
59—*Saracenaria schencki*
60—*Sigmoilina reedi*
61—*Siphogenerina multicostata*
62—*S. nodifera*
63—*Spiroplectammina gracilis*
64—*Uvigerina kernensis*
65—*Verneuilina* cf. *compressa*
66—*Anomalina californiensis* (5)
67—*Bulimina rinconensis* (89)
68—*Cancris sagra* (105)
69—*Cibicides crassiseptus*
70—*Clavulina communis*
71—*Cyclammina clarki*
72—*C. incisa*
73—*Dentalina adolphina*
74—*D.* cf. *multilineata*
75—*Eponides umbonatus*
76—*Gaudryina atlantica*
77—*Lagena substriata*
78—*Lenticulina convergens*
79—*Nodogenerina cienegaensis*
80—*N. lohmani*
81—*N. sanctaecrucis*
82—*Nodosaria acuminata*
83—*N. arundinea*
84—*N. parexilis semlifera*
85—*Plectofrondicularia coshei*
86—*P.* cf. *packardi*
87—*Robulus* cf. *clypeiformis*
88—*Tritaxilina colei*
89—*Uvigerina auberiana*
90—*U. beccarii*
91—*U. hispida*
92—*U. mexicana*
93—*Valvulinaria castitasensis*
94—*Virgulina bramlettei*
95—*Angulogerina occidentalis* (4)
96—*Bulimina carnerosensis mahoneyi* (74)
97—*Ellipsolagena ventricosa*
98—*Eponides affinis*
99—*Lagena sulcata apiculata*
100—*Siphogenerina pseudococoaensis*
101—*S. smithi*
102—*Spiroplectammina coreyi*
103—*S. kewi*
104—*Trochammina parva*
105—*Uvigerinella sparsicostata*
106—*Anomalina glabrata* (6)
107—*Clavulina flintiana*
108—*Gaudryina* cf. *flinti*
109—*G. gracilis*
110—*Marginulina dubia*
111—*Siphogenerina mayi*
112—*Dentalina* cf. *guttifera*
113—*Bolivina marginata adelaidana*
114—*Clavulina humilis mexicana*
115—*Eponides nanus*
116—*Gaudryina atlantica asperita*
117—*G. lobatula*
118—*G. subrotundata*
119—*Lagena perlucida*
120—*L. semistriata*
121—*Planulina appressa*
122—*Plectofrondicularia miocenica laimingi*
123—*Siphogenerina tenua*
124—*Anomalina* cf. *patella* (8)
125—*Bulimina pyrula* (88)
126—*Dentalina quadrulata*
127—*Lagena costata*
128—*L. hexagona scalariformis*
129—*Pulvinulinella subperuviana minuta*
130—*Robulus* cf. *nitidus*
131—*Plectofrondicularia miocenica directa*
132—*Bolivina* aff. *advena* (23)
133—*Cibicides relizensis*
134—*Bolivina perrini*
135—*Bulimina pseudoaffinis*
136—*B. subcalva*
137—*Lagena aculicosta*
138—*Planularia luciana*
139—*P. baggi*
140—*Robulus reedi*
141—*R.* aff. *simplex*
142—*Valvulineria williami*
143—*Baggina cancriformis* (12)
144—*Dentalina insolita*
145—*Siphogenerina hughesi*
146—*Nodogenerina advena hughesi*
147—*Pullenia* aff. *miocenica*
148—*Robulus branneri*
149—*Buliminella hesrvana* (100)
150—*Cancris baggi* (103)
151—*Gyroidina relizana*
152—*L. apiculata*
153—*L. globosa*
154—*Lenticulina relizensis*
155—*Nonion umbilicatus*
156—*Quinqueloculina* cf. *oblonga*
157—*Q.* cf. *seminula*
158—*Rotalia beccarii*
159—*Uvigerinella californica gracilis*
160—*Anomalina salinasensis* (9)
161—*Bulimina pseudotorta* (87)
162—*Dentalina obliqua*
163—*Nodosaria tornata*
164—*Pullenia miocenica*
165—*Robulus miocenicus*
166—*R. smileyi*
167—*Uvigerina proboscidea* (?)
168—*Valvulineria californica obesa*
169—*V. ornata*
170—*Baggina robusta globosa* (14)
171—*Flabellina crassa*
172—*Lagena crenata*
173—*Rotalia orbicularis*
174—*Bolivina imbricata inflata* (42)
175—*Cassidulina williami*
176—*Planularia dubia*
177—*Pullenia miocenica globula*
178—*Siphogenerina reedi*
179—*Uvigerinella nudocostata*
180—*U.* aff. *obesa*
181—*Valvulineria californica*
182—*V. miocenica*
183—*Bolivina dunlapi* (34)
184—*Bolivina tumida cuneata* (69)
185—*Buliminella* aff. *californica* (96)
186—*Cassidulina* cf. *pulchella*
187—*Dorothia californica*
188—*Siphogenerina collomi*
189—*S. nuciformis*
190—*Uvigerina joaquinensis*
191—*Valvulineria joaquinensis*
192—*Bolivina marginata gracillima* (48)
193—*Bulimina galliheri* (77)
194—*Eponides rosaformis*
195—*Pullenia moorei*
196—*Dentalina barnesi*
197—*Nodogenerina irregularis*
198—*Pulvinulinella capitanensis*
199—*P. gyroidinaformis*
200—*Baggina subinaequalis* (15)
201—*Bolivina modeloensis* (49)
202—*B. sinuata alisoensis* (61)
203—*B. licensis* (67)
204—*Bulimina uvigerinaformis* (93)
205—*Cassidulina monicana*
206—*Cibicides altamirensis*
207—*Eponides* aff. *healdi*
208—*Nonion pizarrensis multicameratus*
209—*Robulus mohnensis*
210—*Siggrunda californica*
211—*Uvigerina carmeloensis*
212—*Virgulina californiensis tiosaensis*
213—*V.* cf. *schreibersiana*
214—*Bolivina decurtata* (33)
215—*B. subadvena* (?)
218—*Nonion monterreyanus carmeloensis*
219—*Uvigerina madeloensis*
220—*Bolivina barbarana* (27)
221—*B. pseudospissa* (55)
222—*Chilostomella* cf. *ovoides*
270—*Siphidium hughesi*
271—*Rotalia garretyanis*
272—*Cibicides floridanus*
273—*Calvulina patens*
274—*Cyclammina cancellata obesa*
275—*Haplophragmoides trullisatus*
276—*Marginulina subbullata* (?)
325—*Bolivina parva* (51)
326—*Bulimina monterreyana delmontiensis* (61)
327—*Planulina ornata*
328—*Eponides exiguus*
329—*Uvigerina subperegrina*
330—*Valvulineria araucana*

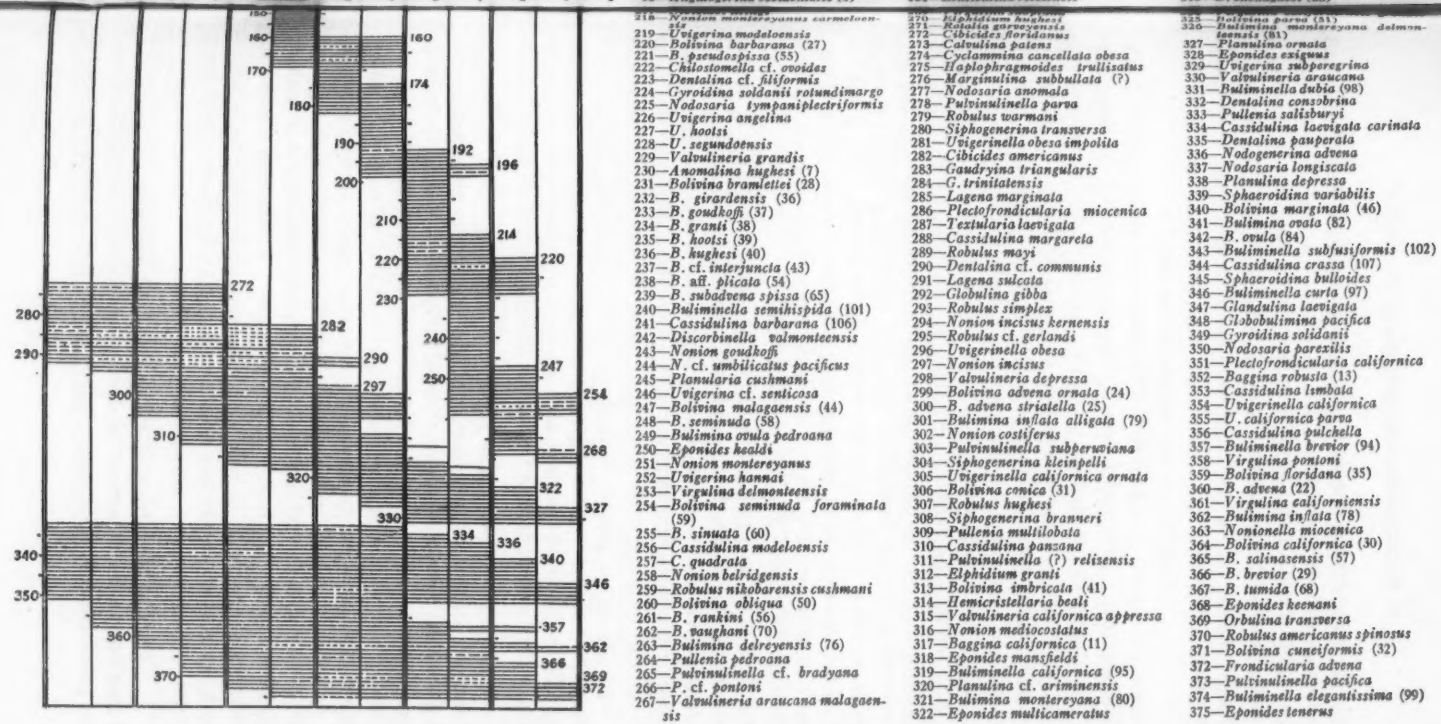


FIGURE 9.—*Range chart showing known stratigraphic occurrences of Foraminifera in Miocene deposits of California, grouped according to distribution*

(Data from R. M. Kleinpell). This figure shows one of several possible ways of plotting data on the distribution of foraminiferal species so as to express graphically significant observations on zonal arrangement of the fossils. The diagram would be improved greatly by variation in the weight of lines to denote relative abundance. (Dashed lines indicate uncertain identification; dotted lines indicate absence of record between older and younger occurrences reported; thickness of lines indicates relative abundance. Numbers in parentheses following names of species indicate placement in Figure8.)

Kleinpell's highly valuable work was selected for study because of its comprehensive scope and because it is the basis for definition of six stages (Zemorrian to Delmontian) introduced in the California Tertiary column. To appraise the paleontological evidence furnished by Foraminifera for establishment of the time-rock divisions proposed by Kleinpell, grouping of ranges according to stratigraphic occurrence was judged to be needful.

and remiss in recording data as to sources; many amateurs dissipate their collections by sale or exchange with other amateurs.

Utilization of all possible techniques for improving the quantity and quality of fossils by methods of washing, concentration, chemical or mechanical preparation, and best possible means for mounting, sectioning, and illustrating will add to the volume and value of research.

ORGANIZATION AND RECORDING OF DATA

Paleontological literature is replete with ill-recorded and poorly organized paleontological information. This relates especially to papers that seek to present information on the stratigraphic occurrence of fossils. Publication of numerous formidable-looking faunal lists, which are presumed to inform readers on the makeup of fossil assemblages, often means little, even to another paleontologist, unless significant elements of the assemblage are discriminated in some way and their presumed significance made clear. If identification of species can be relied on, they have value as records, but often the identifications are worthless. Many such lists are unaccompanied by information on relative abundance of the forms recognized. The paleontologist who thinks he has finished his task after compiling a faunal list has no comprehension of proper objectives in his work. By and large, I am disposed to reckon the value of most unannotated faunal lists and tables as little more than zero, which means that they probably are not worth the paper space occupied—let alone the not inconsiderable expense of setting them in type.

Specially in need of improvement are faunal tables which undertake to summarize data on the composition and distribution of fossils by horizon and locality. Most of us paleontologists have done a poor job of selling our wares. We do not give adequate attention to interpreting and explaining our data. The meaning of faunal summaries presented in tabular form may have great importance, but generally this meaning is effectively concealed by the manner in which the table is organized. Study of ways in which significant data are made apparent at a glance seems urgently needed. Effort along this line is illustrated here by a study of the distribution of Miocene Foraminifera in California as recorded by R. M. Kleinpell (1938) (Figs. 8, 9).

PREPARATION OF REFERENCE WORKS

The volume of accumulated information on systematic and stratigraphic paleontology is already so great that organization of knowledge is difficult, even in the hands of specialists working in restricted fields. Literature is bulky and widely dispersed. Both for use in training new workers and for aid to all engaged in paleontology, there is great need for comprehensive reference works consisting of bibliographies, periodically revised editions of textbooks stressing morphology and classification of fossil groups, and stratigraphically arranged summaries of pertinent paleontological data with subordinate citation of regions. Preparation of such compilations, including summaries of knowledge or judgment, is a task that can be accomplished only by extensive and effective collaboration, which for many reasons is not easily arranged. Need, however, grows from year to year.

CRITICAL SURVEYS OF SELECTED STANDARD SECTIONS

Finally I may suggest the importance of developing much more detailed and carefully studied paleontological information that is closely tied to selected sections of

fossil-bearing rocks that may be used as standards of reference in various regions. Taken together, these sections should cover all parts of the column. Such critical surveys, when completed, will assuredly constitute invaluable yard sticks or anchoring posts around which further studies in stratigraphy and paleontology may be centered. At present there is too little knowledge of the paleontologic content of most of our standard stratigraphic sections.

CONCLUSION

In summation, I suggest that stratigraphical paleontology comprises the good red blood of geology, which, coursing through heart and arteries, animates and energizes all parts of the body. There is no substitute for this life-giving fluid, and it is all-important that circulation of the paleontological blood stream should be healthy and strong. I see no sign of any serious infection or trouble like leukemia. Certainly we have no reason to fear clotting that may produce coronary thrombosis. The unfavorable symptoms which I discern seem to be those belonging to anemia, and I am concerned that we find quickly the proper dosage of vitamins and other dietary remedies. Surely, these can be supplied.

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BULLETIN OF THE GEOLOGICAL SOCIETY OF AMERICA
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PUSHING BACK THE HISTORY OF LAND MAMMALS IN WESTERN NORTH AMERICA

BY CHESTER STOCK

(Address as Retiring President of the Society of Vertebrate Paleontology)

Permit me to express on behalf of the Society of Vertebrate Paleontology the pleasure that our organization takes in the opportunity to meet this year in Canada as one of the several societies affiliated with The Geological Society of America.

Within the time allotted to me I should like to outline briefly the advances made in recent years in a study of the vertebrate paleontology of the West, pointing out its bearing on historical geology and wherein the acquisition of new knowledge has come as a result of penetration of the older Tertiary rocks of this region.

We are indebted primarily to the late John C. Merriam for the foundations of our knowledge concerning the Tertiary stratigraphy and vertebrate paleontology of the Pacific Coast and Great Basin paleontological provinces of western North America, for it was he and his graduate students at the University of California during the period from about 1900 to 1918 who were responsible for many of the contributions to those fields of research. This activity on the part of the men associated with him continued with his aid after Doctor Merriam became president of the Carnegie Institution of Washington.

It was Merriam who recognized the significance of these contributions as they relate to geological correlation studies, for he clearly saw the opportunity of bringing the Tertiary marine faunas of the Pacific littoral in their correct time relationship, insofar as that was possible, to the fossil vertebrate assemblages known from the continental interior of North America. This became possible from discoveries made for the most part by his students of horizons containing the remains of later Tertiary mammalian faunas intercalated in sections largely comprised of marine formations in the Coast Ranges of California. Forming an integral part of these correlation studies were also the discovery, description, and age determination of a number of vertebrate faunas collected in later Tertiary strata in the western portion of the Great Basin paleontological province.

We would be seriously remiss in making a statement of these accomplishments were we not to call attention to the efforts of the pioneers who contributed so much paleontological information on the basis of study of collections obtained at localities that had been discovered many years before. Thus, the investigations of Cope, Marsh, Wortman, and others drew attention to the rich fossil mammalian material that had been found in the John Day basin of north-central Oregon, but it was Merriam who in 1902, as a result of extended field work, clarified the stratigraphic relations of the deposits that furnished the paleontological record. Moreover, Merriam and Sinclair clearly defined for the first time the constituency and age relationships

of the individual mammalian faunas. In the present review mention must be made also of the finds of fragmentary fossil mammalian remains in the gold-bearing gravels and associated sediments of the Sierra Nevada, made during the Second or Whitney Geological Survey of California, and subsequently described by Leidy.

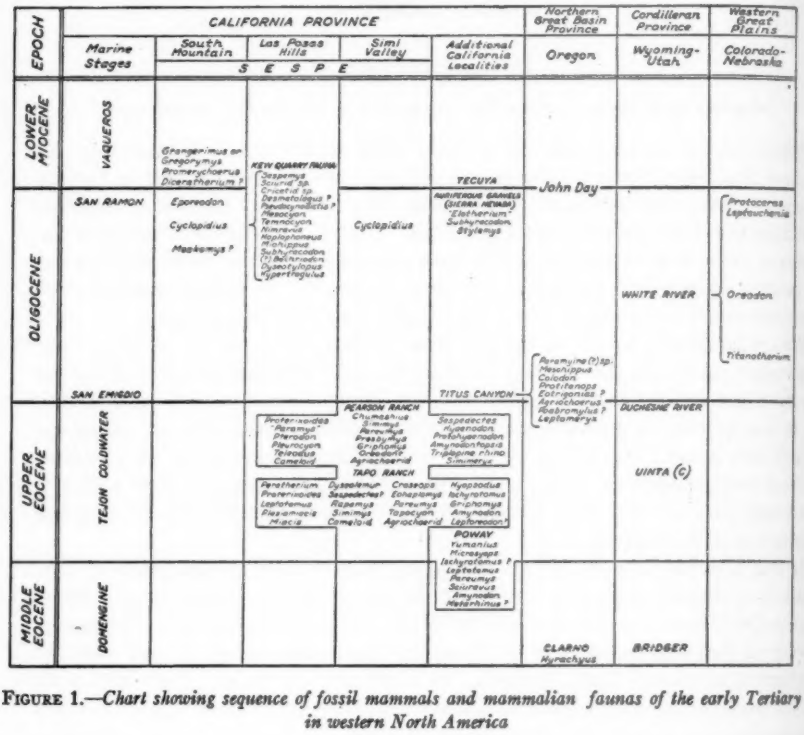

FIGURE 1.—*Chart showing sequence of fossil mammals and mammalian faunas of the early Tertiary in western North America*

As a result, our knowledge of the Tertiary mammalian history of western North America was increased considerably for the Pliocene, Miocene, and for the late Oligocene (the latter age being included in the present statement on the assumption that the faunas from the John Day formation are, at least in part, Oligocene and not lower Miocene).

Beginning with the year 1920 land vertebrates of either lower Miocene or upper Oligocene age were described from the Coast Ranges of California. Almost immediately there followed the discovery of mammalian fossils in the Sespe. This striking, vari-colored, continental formation, in places from 6000 to 7000 feet in thickness, forms a well-defined unit in the stratigraphic column exposed in the southern Coast Ranges and in the Santa Monica and Santa Ana mountains of California. The Sespe lies between the marine Vaqueros formation of lower Miocene age and the marine Domengine of the middle Eocene. In places the Sespe is conformable with

the Vaqueros above; at other localities it appears to be conformable with the marine Eocene below.

Paleontological exploration of the Sespe has brought to light a surprising number of fossil mammalian species, representing four stages in time (dating from lower Miocene to upper Eocene inclusive). Detailed descriptions of many of these fossil mammals have appeared in printed articles. From three of these horizons come assemblages comprised of a variety of mammalian types. These faunas in their order of descending age are: (1) the Kew Quarry, (2) the Pearson Ranch, and (3) the Tapo Ranch. The Kew Quarry fauna consists of an association of fossil mammals, some showing close relationship with comparable forms in the John Day (Arikareean), others related to types known from the upper White River deposits (Whitneyan stage) of the western Great Plains. There can be no question as to the contemporaneity of the several kinds of mammals that constitute the Kew Quarry fauna. The next older assemblage, namely the Pearson Ranch fauna, finds its nearest age equivalent in, but is noticeably different ecologically from, the fauna of the Duchesne River formation of the Uinta Basin. It is referred to the uppermost Eocene (Duchesnean). Lastly, the Tapo Ranch fauna is definitely more primitive and older than that from the Pearson Ranch. The Tapo Ranch is correlated in time with the assemblage from the Uinta C horizon (Uintan) of Utah but is likewise different ecologically from the latter. It is regarded as upper Eocene.

A study of the vertebrates from the Sespe has given rise to certain impressions as to the nature of the environmental conditions that prevailed during the time range of accumulation of this formation. That these conditions changed from the upper Eocene to the lower Miocene is clearly indicated by the faunal turnover. That the climate altered from one with presumably considerable rainfall in the Eocene to one of apparently less precipitation in the upper Oligocene is strongly suggested by the individual types that comprise the congeries of mammals found in the successively higher horizons of the Sespe. Unfortunately for this generalization it is not yet possible to utilize information derived directly from lower Oligocene faunas of the Sespe.

It is a curious fact that, while in some sections there is a stratigraphic sequence of several thousand feet without recognizable interruption in the Sespe formation below the beds containing the upper Oligocene faunal stage, no counterparts of the fauna of the lower Oligocene *Titanotherium* zone (Chadronian) have been found. Indeed, nearest approach in age to the *Titanotherium* fauna of the lower White River is the mammalian assemblage from the Titus Canyon formation of southeastern California. The Titus Canyon deposits were described by Stock and Bode and are exposed along the flanks of the Grapevine and Funeral mountains between Death Valley and the Amargosa Desert. Description of the entire fauna has been completed and is now in press. The assemblage is clearly more primitive and is older than that known from the typical Chadron. The Yoder formation described by Schlaikjer from Wyoming presumably occupies a position similar to that of the Titus Canyon, but the fauna from the latter beds contains a few more kinds of earlier mammals than in the Yoder assemblage. In contrast to the Chadron fauna, the

Titus Canyon has some mammalian elements in it that are closely related to forms in the Duchesne River or in the Eocene. With regard to the age of the Titus Canyon fauna it is of more than casual interest to point out that, while later Tertiary vertebrate faunas (those of Pliocene and Miocene age) are not uncommonly found in contin-

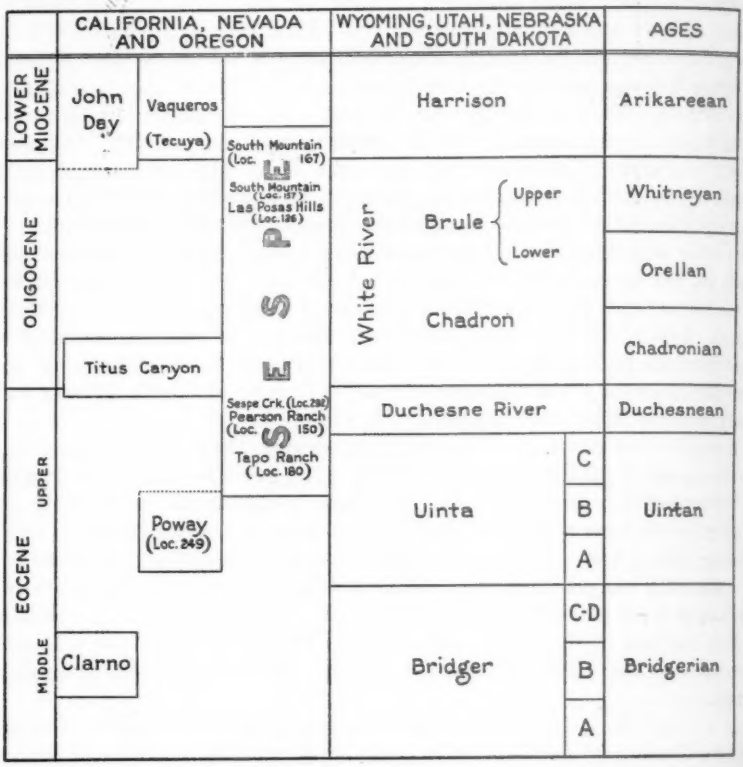

FIGURE 2.—*Correlation chart showing relationships of early Tertiary mammalian faunas of western North America*

ental deposits of eastern California and western Nevada, those of the earlier Tertiary, with the exception of the Titus Canyon, are, as yet, singularly unknown. This paucity of record probably reflects the occurrence of important diastrophic events that transpired in the western part of the Great Basin province before and after the early Tertiary.

Returning now to thePacific Coast province, the oldest Tertiary mammalian assemblage yet discovered is that from the Poway conglomerate and sands in and about the city of San Diego in the southwestern part of California. The Poway sediments rest on the marine Rose Canyon shale. The fossil molluscan assemblage from the Rose Canyon is of the same age as that of the Tejon upper Eocene.

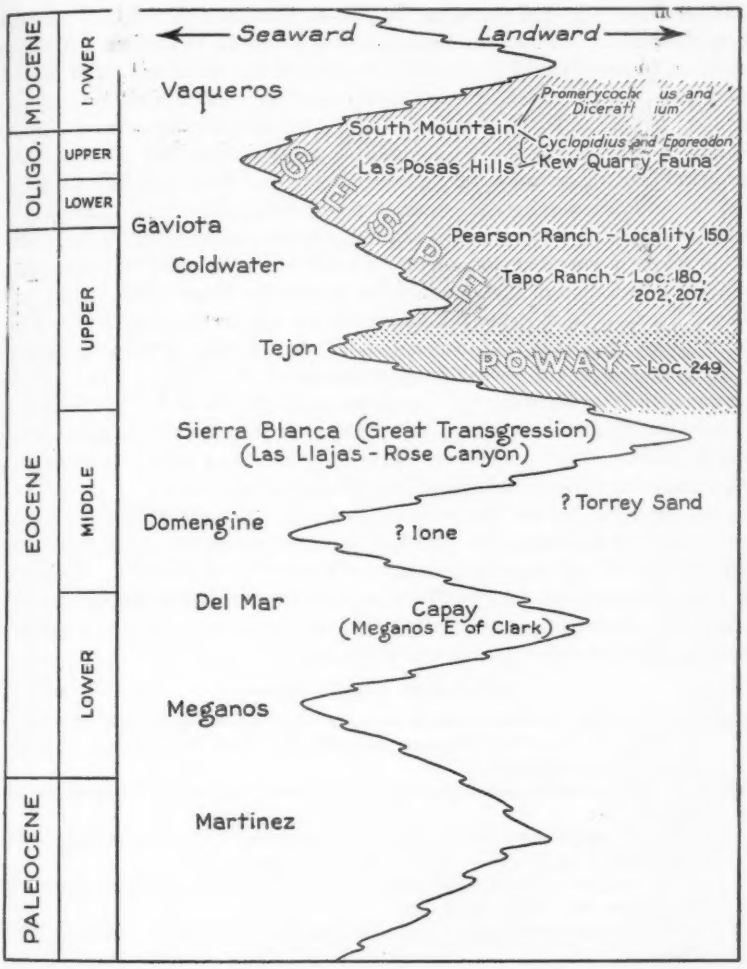

FIGURE 3.—*Chart showing relationships of the mammalian faunas from the Sespe and Poway to the marine transgressions in the Californian region*
Chart constructed with the aid of Professor U. S. Grant IV.

The Poway vertebrate fauna is related to that of the Tapo Ranch Sespe, but certain of its fossil mammals appear to belong to an earlier stage of development. The assemblage, as a matter of fact, is regarded as immediately post-Bridger (that is, post-middle Eocene) in age. It is the oldest known Tertiary mammalian fauna at present recorded from the Pacific Coast province.

In this connection it may be of interest to note that, while search has been made, as yet no Paleocene mammalian remains have been found in sedimentary formations

of the far West. Several years ago Dr. W. P. Woodring of the U. S. Geological Survey directed my attention to some land-laid sediments in the Santa Ana Mountains which he regards as of the same age as strata of the Martinez marine Paleocene of California. Unfortunately, these deposits have not yielded fossil vertebrates. I have been impressed by what appears to be a curious paradox—namely, that the thickness of Paleocene strata in California, in comparison to that of Eocene formations found here, represents a more abbreviated unit of time than that, for example, found in the Paleocene-Eocene sequence of the Rocky Mountain province. Is it possible that strata now assigned to either the lower Eocene or to the upper Cretaceous in the marine stratigraphic column of California are in reality Paleocene in age? However, a discussion of this question lies beyond the scope of the present paper.

The oldest fossil land mammal known from the western part of the Great Basin province is an early type of rhinoceros, similar to a Bridger species, recognized by Dr. R. A. Stirton in the lower Clarno sediments of the John Day basin, Oregon. Long ago named by Merriam, the Clarno was considered to be Eocene in age on the kinds of fossil plants it contains. The present age identification based on a single tooth, if substantiated by additional material, presents an earlier stage within the Eocene than that hitherto recognized for this part of the Clarno.

In recapitulation, we see that in recent years, with the availability of rather representative fossil collections for the most part, the vertebrate paleontologist finds it possible to push back mammalian history in western North America. The penetration of the Tertiary from the lower Miocene well into the Eocene not only establishes a number of new and significant paleontological facts, but likewise aids in better understanding of the geologic history of the region.

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INDEX MAP OF THE DEATH VALLEY REGION

From Noble (1941). Show southern half of Furnace Creek sheet and northern half of Avawatz Mountains sheet. Area labelled Plate 2 is the Tecopa area, of this report. Area labelled Plate 3 and line of section A-A′-A″-A‴ refer to Virgin Spring report of Noble (1941).

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GEOLOGY OF THE TECOPA AREA, SOUTHEASTERN CALIFORNIA

BY JOHN F. MASON

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ABSTRACT

This paper presents the areal geology of the Tecopa area, which may be the root zone of the Amargosa thrust and other sheets described in the Death Valley (Virgin Spring) region, California (Noble, 1941). The stratigraphy of the Algonkian and Cambrian strata in the Tecopa area was studied by Hazzard assisted by the writer. The present map (Pl. 2) is an attempt to utilize the published stratigraphic units of Hazzard and Hewett as cartographic units, in parts of the Shoshone and Tecopa quadrangles, southeasternmost Inyo County, California. More than 16,000 feet of Cambrian and Algonkian strata is involved in structural complexity suggesting westward thrust faulting on a large scale. The sedimentary section apparently has been skidded off the rigid Archean basement, and similar skidding of younger over older beds occurs higher in the section at two or three horizons. Movement in nearly all cases seems to be to the west, a fact not yet harmonized with directions of movement reported in neighboring areas. High-angle faults, including those of the Basin Range faulting, are mapped.

INTRODUCTION

For several years the U. S. Geological Survey has sponsored an investigation of the Death Valley area, in the northern half of the Avawatz Mountains quadrangle and the southern half of the Furnace Creek quadrangle, southeastern California. The major problems are: the composition of the Archean, the stratigraphy of the Algonkian, of the Paleozoic, and of the Tertiary and Quaternary (including products of igneous activity), and the effects of the Cenozoic diastrophism (including thrusting on a major scale). Noble (1934; 1941) has dealt especially with the Algonkian stratigraphy and the effects of Cenozoic diastrophism. Because of the writer's familiarity with the Paleozoic strata in the Nopah Range, Noble encouraged him to map the distribution and study the structural behavior of the Paleozoic rocks in the Tecopa area.

The Tecopa area, in the southeasternmost corner of Inyo County, California, is included in the northeastern portion of the Avawatz Mountains topographic sheet[1]. It comprises approximately 230 square miles of Basin and Range country, midway between the Spring Mountain Range and the Death Valley trench.

PREVIOUS INVESTIGATIONS

Spurr (1903, p. 195–200; Pl. 1) incorporated Rowe's reconnaissance observations in the "Kingston" (=Nopah) Range in a geological reconnaissance map. The area of the present report is likewise represented on the geologic map of Inyo County of Waring and Huguenin (1915) and on the geologic map of California, published in 1938 by the California State Division of Mines. Tucker and Sampson (1938) commented briefly on the geology. Various specialized reports on nitrates and borates deal only incidentally with the general geology (Campbell, 1902; Noble, Mansfield, *et al.*, 1922; Noble, 1926; 1931).

The first published result of the Death Valley investigation was a brief statement on the stratigraphy (Noble, 1934) which led to the detailed work of Hazzard (1937a) on the Paleozoic stratigraphy of the Nopah region. The writer was associated with Hazzard in some of this field work and has utilized information obtained at that time in the preparation of this report.

Noble (1941) has outlined the general geology of the Death Valley region and has described the unusual structures.

ACKNOWLEDGMENTS

The writer deeply appreciates the suggestion of problem by Dr. Levi Noble and his continuing interest and advice. Mr. James B. Knight, Jr., assisted in the fieldwork, which was facilitated by the courtesies extended by Mr. Charles Brown and his family, of Shoshone. Field equipment was loaned by Princeton University. The writer thanks the members of the Faculty of the Department of Geology of

[1]The U. S. Geological Survey has named the quadrangle bounded by Lat. 35°45′ and 36° and Long. 116°00′ and 116°15′ the Tecopa quadrangle, and the 15 minute quadrangle adjacent to the west, the Shoshone quadrangle. Plate 2 encompasses most of the area within the Tecopa quadrangle and part of that in the Shoshone quadrangle.

Princeton for suggestions and advice during the preparation of the report. Miss Anne Shafer, of the Academy of Natural Sciences, Philadelphia, assisted in typing the manuscript. The writer was aided in the preparation of the map and sections by Mr. George W. Stose and by Mr. P. L. Mattox, of the U. S. Geological Survey. Finally, he expresses his appreciation of financial assistance from the Van Ingen research funds of Princeton University.

GEOGRAPHY

The Tecopa area and surrounding region, shown on Plate 1, are readily accessible. Three mountainous groups in the area mapped are: the Nopah Range, the Resting Springs Range, and the Dublin Hills. The Nopah Range, a rugged homoclinal uplift in the eastern part, extends north-south across the mapped area. The ridge line is 5800 feet above sea level, and the flanking valleys 1700 to 2500 feet. Slopes are steep and barren, except for gnarled junipers and sparse grass. The Resting Springs Range rises to 3260 feet near the center of the north edge of the map and declines south-southeastward to a vanishing point near Resting Springs. Its western face is surprisingly rugged and more barren than the Nopah Range. The Dublin Hills is a sprawling group of barren rugged hills, rising to 3085 feet from surrounding valleys at 1500 to 2100 feet.

A group of low hills with a 1715-foot bench mark just north of Tecopa is here termed Tecopa Hot Springs Hills, from the well-known thermal spring at their north end. The Tecopa area is in the Middle Amargosa Basin, as described by Thompson (1929, p. 572, 575). The master stream is the Amargosa River, which heads more than 90 miles north of Shoshone and flows across the western portion of the area south-southeastward. A large unnamed tributary, which enters the Amargosa at Tecopa, begins in the large valley between the Nopah and the Resting Springs ranges. Another, entering between Tecopa and Zabriskie, drains the valley up which the Zabriskie-Greenwater road goes. The area of the Nopah Range drains via Tule Holes and "Old Smelter Well" (locally called Hank's Place) down the canyon called Willow Creek on some maps, past China Ranch, and into the Amargosa at Acme.

STRATIGRAPHY

The stratigraphic column in the Death Valley area includes Archean, Algonkian, Cambrian, Ordovician, Silurian, Devonian, Carboniferous, Tertiary, and Quaternary deposits. In the Tecopa area, no post-Cambrian Paleozoic rocks, except a few Carboniferous, are present. The three Algonkian units recognized occur in various parts in small amounts. The Lower and Middle Cambrian units are, on the other hand, very well developed.

The formation recognized in the Tecopa area are listed in Table 1, with their thicknesses and descriptions. Hazzard (1937a) has discussed the entire Paleozoic section. For generalized regional stratigraphy, including distribution, Noble's two résumés are invaluable (1934; 1941). No purely stratigraphic work was undertaken in the present research because the problems of correlation have been covered by Hazzard and Noble. The formations utilized are mapping units, whose relative

TABLE 1.—*Summary of exposed rock formations in the Tecopa area, California*

Age	Formation	Approximate maximum thickness (feet)	Description	Occurrence	References
QUATERNARY	Alluvium (Qal)		Unconsolidated heterogeneous sand, gravel and boulders	In alluvial fans, gravel terraces, and debris in intermittent stream channels	
	~~Unconformity~~~				
	Gravel beds (Qg)	400?	Heavy gravel and cobble beds, partly consolidated, representing fanglomerates	Exposed in vertical cliffs 300 feet high along Amargosa River south of Tecopa. Dips from 3° to 13° may be largely primary. Base on China Ranch beds unconformable; probably similar relation to Lake beds (Qlb)	
	~~Unconformity~~~			?Unconformity near Tecopa	
	Lake beds (Qlb)	400	Greenish- to light-brown partly calcareous clay and sandstone, lacustrine. Saline content less than in older China Ranch clays. Bones of a Pleistocene elephant were found near Shoshone	Extensively exposed in Amargosa depression and Chicago valley. Nearly horizontal, only slightly disturbed by minor faulting (unmapped) and faint warping. This attitude, together with terraces cut on hills near Tecopa Hot Springs, the notable constriction of the Amargosa depression south of Tecopa, and general history of Mohave Desert region suggests that these beds are evidence of a Pleistocene lake, similar to Lake Manix	Noble, Mansfield, *et al.*, 1922, p. 61–6; Noble, 1931, p. 62–71; Noble, 1934, p. 176; Noble, 1926, p. 67–70; Buwalda, 1914
	~~Unconformity~~~			Unconformity exposed near Shoshone	
	Basalt (Qb)	100	Conspicuous black basaltic flows	Cut by faulting, if somewhat doubtful correlations are accepted. Noble (oral communication) states that his long investigation suggests that these flows are equivalent to those elsewhere included in the Funeral fanglomerate. Unconformably overlying Cambrian north and southwest of Shoshone	Noble, 1941, p. 957
	(non-sequence)				
	China Ranch beds (Qcr)	1200	Light-colored saline clays, with bedded gypsum; of lacustrine origin	Unconformably overlain by Quaternary gravel beds (Qg); relation to basalt (Qb) and lake beds (Qlb) not evident. Noble (personal communication)	Noble, Mansfield, *et al.*, 1922, p. 67–

	(non-sequence)			west of Shoshone	
	China Ranch beds (Qcr)	1200	Light-colored saline clays, with bedded gypsum; of lacustrine origin	Unconformably overlain by Quaternary gravel beds (Qg); relation to basalt (Qb) and lake beds (Qlb) not evident. Noble (personal communication) indicates the China Ranch beds are unconformably below the lake beds (Qlb) and suggests Pliocene? age	Noble, Mansfield, *et al.*, 1922, p. 67–85
	~~Unconformity~~			Angular unconformity	
	Volcanic sediments (Tm)	1500?	Light-colored heterogeneous sediments mainly of volcanic origin, including tuffs, breccias, coarse and fine clastic deposits, and lake beds; bedding irregular	Exposed in thrust-faulted area south of Tecopa. Relation to volcanics near Shoshone (Tv) not determined; possibly equivalent, for these beds similarly are the youngest involved in thrusting in their vicinity. Base not exposed	
LATE TERTIARY	(non-sequence)				
	Volcanics (Tv)	1000+	Fresh volcanic flows and tuffs, mostly glassy and acidic	Top generally concealed by alluvium, as on east flank of Resting Springs Range and east of Nopah Range. Youngest unit involved in thrusting locally. Compared by Noble (personal communication) with Pliocene? rhyolitic and andesitic flows and tuffs near Greenwater, 16 miles northwestward. North of map area and on west side of Resting Springs Range, these volcanics unconformably overlie beds containing borate deposits such as are characteristic of Miocene Furnace Creek formation elsewhere in Death Valley area	
	(non-sequence)				
CARBONIFEROUS	Monte Cristo (?) formation (Cmc)	400+	Dark-gray limestone with thin layers of bedded chert and with white calcite marbling, succeeded by light-gray crinoidal limestone; indeterminable corals and crinoid stems	Exposed in fault blocks on east side of Nopah Range near north edge of map area. More northerly exposure comprises uppermost part of lower member and most of upper member of formation as identified by Hazzard at north end of Nopah Range, where writer has identified Mississippian fossils	Hazzard, 1937a
	(non-sequence)				

TABLE 1.—*Continued*

Age	Formation	Approximate maximum thickness (feet)	Description	Occurrence	References
MIDDLE CAMBRIAN	Cornfield Springs formation (Ecs)	2975	Light- and dark-gray dolomite and dolomitic limestone, with at the base a 135-foot shaly zone, reddish yellow to brownish gray from a distance	Conformable contact with Upper Cambrian at a sudden increase in clay content; exposed farther north in Nopah Range No tectonic discontinuities known	Hazzard, 1937a
				Conformable contact, at a sudden increase in clay content of calcareous series	
	Bonanza King formation (Ebk)	1500	Gray dolomite and dolomitic limestone, unfossiliferous	Exposed in Nopah and Resting Springs ranges, and in hills west of Shoshone. As the base of the great calcareous series, the base seemingly constituted a plane of weakness of localizing movement. Outliers are known on Cadiz, Wood Canyon, and Tertiary formations. Breccia zones parallel to bedding and near base, exposed in southeast part of hills west of Shoshone, may represent additional planes of movement	Hazzard, 1937a
				——Conformable, sharp transitional contact——	
	Cadiz formation (Ec)	700	Transition from sandstones and shales of Wood Canyon to calcareous series above. Sandstone, shale, and limestone, red and green near base; top limestone-shale sequence is distinctive yellow brown. Middle Cambrian fossils in upper beds	In southernmost exposures in Nopah Range, upper contact marked by breccia of overlying formation for more than a mile. Farther north, and in Resting Springs range, no breccia known. West of Shoshone nearly every Cadiz-Bonanza King contact is tectonic and marked by breccia Exposed generally in mapped portions of Nopah and Resting Springs ranges, and in hills west of Shoshone	Hazzard, 1937a
				Conformable gradational contact; chosen by Hazzard at a thin limestone in shales, between Lower and Middle Cambrian fossils	
	Wood Canyon formation	3050	Heterogeneous mass of sand-	Top is normal sedimentary contact in Nopah and	Hazzard, 1937a

					Conformable gradational contact; chosen by Hazzard at a thin limestone in shales, between Lower and Middle Cambrian fossils	
LOWER CAMBRIAN		Wood Canyon formation	3050	Heterogeneous mass of sandstone and shale, with minor quartzite, and notable algal limestone near top. About 630 feet below top is the 160-foot vitreous Zabriskie quartzite. Fossils sporadic in upper 1150 feet	Top is normal sedimentary contact in Nopah and Resting Springs ranges. Near north limit of map in Nopah Range, a light-weathering powdery zone near top might be gouge on bedding-plane fault. Similar gouge in hills west of Shoshone, where upper beds of Wood Canyon are eliminated by low-angle faults, probably localized by lithology near the Wood Canyon-Cadiz contact. Zabriskie member represents latest recurrence of Stirling lithology and conditions	Hazzard, 1937a
					Base chosen at bottom of continuous succession of shaly and sandy beds underlying lowest fossils	
					Large-scale intergradational contact, with arbitrarily chosen horizon separating much Stirling-type rock from mapped Stirling	
		Stirling quartzite (Cs)	2600	Pink vitreous quartzite, with about the midpoint 175 feet of sandstone, shale and dolomite, resembling the Johnnie (?). Unfossiliferous	Exposed along west side of Nopah Range, across its south end, at south end of Resting Springs Range, in hills north and south of Tecopa, and on north edge of hills west of Shoshone	Hazzard, 1937a
					Mapped as conformable, owing to lack of evidence to substantiate Hazzard's suggestion of disconformity	
LOWER CAMBRIAN? (OR OLDER)		Johnnie (?) formation (Cj)	2550	Variable lithology, including sandstone, mostly quartzitic; mudstone; and dolomite with some possibly algal pisolitic and oölitic structures. Outcrop area is dark brown and yellow brown	About 965 feet above base, striking change in resistance to erosion, hard quartzites below, and mudstones, sandstones, and microbreccia above. This last may be due to mylonitization on a concealed plane of movement; or it may be a volcanic ash. Lithology identical on two sides of zone of steep confused dips approximately parallel to strike in Nopah Range, so that no great omission of beds is thought likely in Hazzard's section measured across this outcrop	Hazzard, 1937a Nolan, 1929

TABLE 1.—*Continued*

Age	Formation	Approximate maximum thickness (feet)	Description	Occurrence	References
				Doubtful identification is due to absence locally of distinctive lower Johnnie quartzite of type area. Exposed principally in southern Nopah Range; also on west side of range 5 miles northward, and south of Tecopa	
LOWER CAMBRIAN—*Cont.*				Conformable contact well exposed near Gunsight Mine, where dolomite by rapid increase of sand passes into overlying sandstones	
	Noonday dolomite (Cn)	1500	Massive buff-weathering cream-colored dolomite. Rusty-weathering sand grains, especially in upper part, locally makes evident cross-bedding. Bedding planes obscure	Fracturing and brecciation common, providing loci for ore deposition. Below the surface, uncemented breccia zones are not infrequent. Exposed south of Tecopa and in the Nopah Range	Hazzard, 1937a
	~~Unconformity~~~			Exposed in Ivanpah quadrangle	
ALGONKIAN	Kingston Peak formation (Akp)	not locally available	Breccialike, with reddish-purple mudstone matrix and included angular cobbles of garnetiferous hornfels, greenstone, and quartzite, bevelled and striated; whole mass displays fracture cleavage	Represented by small blocks caught in thrust faulting at south end of Nopah Range. Hazzard suggested a glacial origin, whereas Hewett thought the lithology resembled that of a fanglomerate. Hinds interpreted the Kingston Peak as regolith at base of local Algonkian	Hazzard, 1937b; Hewett, 1940; Hinds, 1935
				Undisturbed contact not observed	
	Beck Spring dolomite (Abs)	200+	Gray bedded dolomite, with some nodular markings of possible algal origin	Upper contact is a thrust fault Exposed near Amargosa River south of Tecopa	Hewett, 1940

TABLE 1.—*Concluded*

	Sc			Some nodular markings of possible algal origin	Exposed near Amargosa River south of Tecopa	

TABLE 1.—*Concluded*

					Conformable contact exposed	
	Pahrump	Crystal Spring formation (Acs)	1000	Quartzite, arkosic sandstone, mudstone, shale, and massive, partly algal dolomitic limestone	Sills elsewhere characteristic not present locally Exposed at the south end of the Nopah Range, and near the Amargosa River south of Tecopa Basal conglomerate absent, probably eliminated by thrusting	Hewett, 1940
		Unconformity			Indicated by difference in grade of metamorphism	
ARCHEAN		ARgn		Granite gneiss, characterized by biotite and by porphyroblasts of pink feldspar; weathers dark gray	Upper contact is a thrust fault, permitting direct observation of Ep-Archean surface. Exposed in two areas at south end of Nopah Range	

ages are known for the most part. Doubtful sequences may be confirmed or rectified by mapping in adjacent areas.

STRUCTURAL GEOLOGY

The Tecopa area lies to the east of Death Valley in such a position as to be a "root" area for the west-going thrusts there (Noble, 1941, p. 996). Presumably, the source of thrust plates in the Death Valley area composed largely of Cambrian or Algonkian rocks may be sought in the Tecopa area. The Laramide diastrophism so well represented by east-going thrust sheets in the Spring Mountains and in the Goodsprings quadrangle to the east may have severely affected the Tecopa area, but traces are nearly lost in the present complexity.

The area includes exposures of pre-Cambrian, Cambrian, and Tertiary formations in a series of east-dipping fault blocks that form mountain ranges and hills. Within the hills are exposed numerous thrust and normal faults, for the most part caused by late Tertiary compressive and relaxational stresses.

The writer did not recognize any folds, though Chapin mapped a minor anticline in the China Ranch beds at the southeastern corner of the map area (Noble, Mansfield, *et al.*, 1922, Pl. 34). Noble (1941, p. 959) has pointed out that the remnants of Quaternary basalt flows through Death Valley suggest broad warping. Though folding must be considered in any tectonic history of the general area, the Tecopa area is not favorably placed to establish the facts.

The most recent faulting has blocked out and elevated the present hill masses. In the Basin and Range Province this is termed the Basin Range faulting. Because of its recency, its results are imposing. Within the ranges, certain other faults are but little older and have similar important topographic effects. They are, in part, ascribed to relaxational stresses following compression.

The late Tertiary compression is responsible for most of the faults in the Tecopa area. Some of the faults can be related chronologically to others, but no generally valid sequence has been established. In the compressive spasm, many faults were formed at the same time.

Plate 2 shows some of the faults in vertical section, as tentatively conceived by the writer.

BASIN RANGE FAULTING

The ranges north of the Tecopa area trend north-northwest, and this is continued by the Resting Springs Range. In a number of exposures along the west foot of the range Bonanza King and Cadiz formations are let down by high-angle normal faulting parallel to the range. Similar faulting affected the Nopah Range, where it drops a block of Bonanza King and Cornfield Springs formations to the west foot of the range. In both, the dropped blocks are somewhat broken. These normal faults parallel to the ranges are apparently the latest large movements in the area. These are the only two localities with direct evidence of Basin Range faulting. The Resting Springs Range exposures show a maximum stratigraphic displacement of 1000 feet, while the Nopah Range fault has a stratigraphic throw of about 8000 feet. These

are single examples from a series of similar faults, most of which are hidden by alluvium. Thus the displacements give no generally valid measurement of the complete over-all displacement. Noble (1941, p. 987) suggests that the Basin Range faults are related to the broad warpings indicated by the Quaternary basalt, in which case the faults are not older than Pleistocene.

FAULTING ASCRIBED TO RELAXATION, AND OTHER FAULTING

The northwesterly faults in the Nopah Range are obviously parts of a general system. The northeastern block is consistently the high block. There is thus extension in a northeast direction. In conjunction with the thrusting to the southwest at the south end of the range, the normal faulting may be interpreted as movements of relaxation and adjustment after the thrust compression. Certain low-angle faults on the west flank of the Nopah Range continue across these normal faults. The alluvial valley cutting northwesterly into the Nopah Range across the north edge of the map (Pl. 2) is localized by a normal fault of the general system discussed; no outcrop of the fault was seen. The faulting which discloses the Carboniferous is probably partly of the same system.

The complicated area in the pass over the Resting Springs Range near the north edge of the map area is dominated by northwesterly faults, mostly downthrown on the northeast as in the Nopah Range. However, the narrow slices into which these faults cut the Resting Springs block and the deep penetration of volcanic "slivers" suggest strike-slip movement; but the evidence is not convincing. At least one is a reverse fault, disclosing a thin slice of the Bonanza King in the midst of volcanics.

NORMAL FAULTS TRANSVERSE TO STRIKE OF RANGE

Transverse normal faults ascribed to the late Tertiary compression occur at several points in the Resting Springs Range and the Dublin Hills. In the former the faults are older than the Tertiary volcanics. At the northern edge of the map area, these volcanic rest in depositional contact against a fault plane cutting Wood Canyon, Cadiz, and Bonanza King formations. In the Dublin Hills, there are a number of variously oriented normal faults. At the east foot of the hills two faults bound a small dropped block of Tertiary volcanics resting on the Bonanza King. One mile westward a fault zone with zigzag outcrop slightly east of north separates the main Tertiary volcanic outcrop from the Cambrian area. Northeastward these faults yield to the influence of the westerly normal faults successively up on the north, which are dominant in the hills northwest of Shoshone. That this westerly faulting is not found in the Resting Springs Range is thought significant of the Basin Range dislocations separating major blocks inferred under the alluvium and lake beds of Amargosa Valley.

In the southern Dublin Hills (Pl. 2) and in an outlier to the south, several westerly faults tend to be up successively on the north, the pattern already seen to the north. But near the south end two faults are up on the south. These faults are associated with low-angle dislocations, which may have determined their anomalous movement. Several other westerly faults, up on the north, are related to low-angle dislocations,

suggesting that the two types developed simultaneously. For instance, about a mile northwest of B. M. 3034 a westerly normal fault displaces a low-angle fault separating the Bonanza King formation (above) from the Wood Canyon; the normal fault continues east a quarter of a mile where it turns southward and apparently becomes a low-angle westerly dipping fault putting the Cornfield Springs formation on the Bonanza King. This fault dips more steeply as it continues south and parallels a large northerly normal fault, also down on the west. Both faults are cut off southward by a low-angle fault. Thus their activity must have occurred prior to the (latest) movement on the low-angle fault.

One mile south of this westerly fault another westerly fault displaces a sequence of the Wood Canyon, Cadiz, and Bonanza King downward on the south; its eastern termination is doubtful. North of it the Wood Canyon-Cadiz contact seems disturbed, with certain beds absent and with local brecciation and crushing, and is mapped as a low-angle fault. South of the westerly fault, the base of the Cadiz seems normal, but the top (contact with the Bonanza King) is a low-angle fault. These low-angle faults have resulted in the formation of outliers (klippen) of the Bonanza King. The relations described suggest that westerly normal faults developed contemporaneously with and in response to the same stress as low-angle faults.

FLAWS

There may be no real distinction between the transverse normal faults and the flaws. Lack of full comprehension of the mechanics of the low-angle faults in the Dublin Hills and the possibility of essential differences between the low-angle faults and the thrusts south of Tecopa and in the southern Nopah Range justify discussing them separately. Both types are ascribed to the late Tertiary compressive episode.

East of the Amargosa River and south of Tecopa an easterly normal fault drops the Johnnie formation against Noonday dolomite and Crystal Spring formation. The west end of this fault is deflected by a northwesterly normal fault. In view of its close association with thrust faults, this easterly normal fault is interpreted as a flaw (or tear fault). It may be a normal fault with no strike shift, thus ignoring the adjacent thrust faults. Its cut-out is of the order of 1000 feet (and possibly rotational) in that the Johnnie in one thrust block is thrown against the Noonday dolomite in the next lower thrust block, against the Crystal Spring formation in the lowest thrust block, and against supposedly autochthonous Tertiary sediments.

The northeasterly normal fault at the south end of the Nopah Range is also interpreted as a flaw, though arguments in the preceding paragraph apply here also. The fault seems to die out within the area covered by the Wood Canyon formation. Successively larger displacements are noticed as it crosses the Stirling quartzite and the Johnnie formation; the largest calculated was more than 2000 feet of stratigraphic throw (total thickness of strata missing between adjacent beds on either side of the fault). A comparable displacement is noticeable at the top of the Archean, though precise values are not available. This fault probably cuts the Archean. Moreover, this possibility and the possibility that it is a flaw raise the question whether the Archean is not allochthonous, bounded downward by a thrust.

HIGH-ANGLE NORMAL FAULTS OF POSSIBLE LANDSLIP ORIGIN

In the south end of the Nopah Range are several other normal faults. One drops a narrow slice of the Johnnie formation into the Noonday dolomite and seems to be related to the thrusting characteristic of the pre-Cambrian—Cambrian contact to the southwest. Three faults in the southern Nopah Range are similar in pattern and in displacement, moving blocks of the Lower Cambrian section downward stratigraphically. One fault, to the southeast, moves a block of Wood Canyon formation and Stirling quartzite updip several thousand feet. The fault curves so as to put the middle of the Stirling quartzite against the top of the Johnnie and must therefore be spoon-shaped. Another spoon-shaped fault 2 miles westward drops a block of the Johnnie across the area where the Noonday dolomite was expected and puts the Johnnie against the Archean. Two miles northward another curving fault drops the Johnnie against the Noonday dolomite; a small piece of Noonday dolomite is preserved at the toe of the block, nearly on the (projected) Archean-Noonday contact. The movement on both these faults was of the order of several thousand feet. Unfortunately, information on the precise dips of the planes of these three faults is not available. They may be parts of one large corrugated fault plane, but, because of probable steep dips of the fault planes as well as the absence of corrugated planes on other faults in the vicinity which put younger rocks on older, the writer prefers to consider them landslips. It is supposed that before deposition of the Pleistocene lake beds a deeper excavation of the surrounding valleys, perhaps induced by more pluvial climate, left the range higher than at present, that oversteepening is to be expected, and that spoon-shaped normal faults are the natural results.

The northeasternmost fault on Plate 2 is a similarly curved normal fault, dropping Mississippian (Monte Cristo (?) limestone) against Cambrian (Cornfield Springs (?) formation). The fault plane dips 35° SW. A comparable fault which may be the same one is exposed 1¼ miles southward and puts Mississippian (Monte Cristo (?) limestone) against Cambrian (Bonanza King (?) formation). The fault plane dips 20° SW. This suggests a normal fault dropping Mississippian onto Cambrian strata. This fault is thought to have followed closely the plane of an earlier (Laramide) fault of Cambrian rocks onto Mississippian rocks.

THRUST FAULTS OF OLDER ROCKS ON YOUNGER

Unmistakable thrust faults, putting older rocks on younger, are south of Tecopa, west of Shoshone, and near the northeast corner of the area. One mile south of Tecopa the Algonkian (Crystal Spring) rests on Miocene sediments in exposures on both sides of the Amargosa River. The fault plane dips 21° and 27° SW. and 15° NE., thus suggesting post-thrust warping along northwesterly lines. The thrust block vanishes downdip to the east, and the movement therefore is to the west or southwest. The same fault plane is exposed again 1½ miles southeastward where it is intersected by an easterly normal fault, regarded as a flaw. At each of these localities copious flows of warm borax-bearing water emerge along the fault plane (Noble, 1941, p. 993).

Several outcrops of Cambrian dolomites (Bonanza King) are isolated among

Tertiary volcanics 2½ miles west of Shoshone. From outcrop pattern and direct superposition of Cambrian on Tertiary, and from the lack of a mountain mass from which to derive landslip blocks, these are considered the partly exposed forward edges of thrust blocks. The Cambrian formation is locally badly shattered into blocks a few yards across. At one place the re-entrant pattern of the exposure indicates irregularity of the thrust plane, possibly caused by post-thrust folding. The several exposures do not display an order of movement. Though the mapping suggests that a westerly normal fault intersected one of the Cambrian thrust tongues, the writer thinks the normal fault veers abruptly northward. However, he considers the thrusting in this locality earlier than the westerly normal faulting. The thrust movement was probably northwestward, judging from the map outlines.

In the northeast corner of the map area are two thrusts (or possibly one). One puts Cambrian (Bonanza King) on top of Mississippian (Monte Cristo (?) limestone), the fault plane dipping 75° SW. The other, possibly a continuation of the first, puts Cambrian (Cornfield Springs and Bonanza King) on top of Mississippian (Monte Cristo (?) limestone). The fault plane dips southwesterly. The relations are obscure, but this thrust (or thrusts) seems to have moved eastward, suggesting a Laramide age.

On the west flank of the Nopah Range and near the north edge of the map is a large block of the Bonanza King (and a little of the Cadiz) that rests on the Bonanza King and younger (Cornfield Springs) formations. Erosion through this thrust plate shows the Cornfield Springs formation underneath a southward-dipping thrust plane, above which is the Bonanza King. This thrust plate is cut off at the south by an easterly normal fault with about 5000 feet of stratigraphic cut-out. The normal fault turns abruptly northward near the crest of the range and passes off the map area. Resting on the Bonanza King of the thrust plate, and on the Cornfield Springs of the block under the thrust, and cut off southward and eastward by the normal fault, is another later thrust plate. The Wood Canyon, Cadiz, and Bonanza King formations are exposed. The conclusive evidence of such a plate is that one may see the Bonanza King dolomite in the bottoms of gullies, the walls of which are the Cadiz right side up (for it is succeeded uphill by the Bonanza King). One of these fensters is mapped. Near or at the base of the Bonanza King formation in the younger thrust plate a steep reverse fault strikes northwesterly.

The sequence of events is thought to be as follows: A thrust plate of the Bonanza King and a little of the Cadiz came into the area from an unknown direction (possibly southeast). The normal fault broke through, separating the plate from its roots. The over-steep scarp of the normal fault caused a failure analogous to a landslip, dropping a younger thrust plate (later thrust plate of preceding paragraph) of Wood Canyon, Cadiz, and Bonanza King formations onto the older thrust plate and the block underneath. The reverse fault is ascribed to internal adjustments of the younger thrust plate.

LOW-ANGLE FAULTS

Calling the rocks above the low-angle faults thrust blocks ("younger thrust plate" in preceding paragraph) may not give a correct impression of their significance. In

general the writer approves of the interpretation of these rocks as slipped blocks and the mechanics as those of landslipping. To avoid genetic significance of any term, the legend of Plate 2 contains the noncommittal term low-angle fault.

The largest low-angle fault mapped is beneath the block labelled "Breccia of Cbk and Ccs" on the west flank of the Nopah Range (Pl. 2). The middle Cambrian Bonanza King and Cornfield Springs formations are a jumbled mass resting on the much older Johnnie formation and Stirling quartzite. The main mountain rises to the east, to a crest of Bonanza King formation, with remnants of Cornfield Springs formation on the east flank. The breccia mass rests undisturbed across a normal fault, one of the series previously ascribed to relaxational stresses. Either the block got Cornfield Springs formation from over the crest of the range by thrusting on undetected planes of peculiarly limited distribution, or, before erosion had stripped the Cornfield Springs from the crest of the range, a block of the heavy calcareous series sheared off on a plane cutting upward and eastward from the incompetent base of the calcareous series (Cadiz-Bonanza King contact).

One mile southward a small mass of the Bonanza King rests undisturbed on a fault separating Stirling quartzite from the Wood Canyon formation. This is a slipped block, detached from the Bonanza King at the range crest, and is very likely contemporaneous with the large breccia block northward. In these two instances, the low-angle faulting is later than normal faulting, thought to be relaxational, and therefore later than the late Tertiary compressive episode. No second period of compression is indicated.

Near the south end of the Wood Canyon formation outcrop in the Nopah Range, two areas of that formation are encircled by low-angle faults. These are masses of Zabriskie quartzite, a member near the top, which rest on beds near the base of the formation. The map (Pl. 2) reveals the most likely source as downhill toward the northwest. Close by in this direction, the base of the Bonanza King is extensively brecciated. It is suggested that faults emerged at this horizon, carrying a sheet of which no outliers have been identified. Under the fault there might have been enough drag to put Zabriskie quartzite on the lower Wood Canyon formation. The small patch of the Bonanza King adjacent to the southernmost Wood Canyon may be evidence of the thrust suggested. However, in view of a possible rotation of the Nopah block, emplacing the Zabriskie blocks by gravitative sliding, further evidence is necessary to predicate a thrust.

At the north end of the larger Archean mass in the southern Nopah Range a block of Noonday dolomite and Johnnie formation has been displaced downhill more than 1000 feet and rests undisturbed across the Archean-Cambrian (fault) contact. A small fragment of the Noonday dolomite just northward has been similarly displaced and rests entirely on the Archean. A landslip origin is ascribed to these low-angle faults.

THRUST FAULTS OF YOUNGER ROCKS ON OLDER

The Cambrian—pre–Cambrian contact in this vicinity is a thrust fault as evidenced by the sporadic occurrence along the contact of fragments of the Kingston Peak formation (one of which is mapped), by the brecciation of the Cambrian Noon-

day dolomite, and by the Cambrian Crystal Spring relations at the south end of the range. The relief on the Algonkian beds before Cambrian deposition is not so great as to eliminate the Beck Spring dolomite and Kingston Peak formation. In mining openings uncemented breccias are present at many places near the base of the Cambrian dolomite. The Crystal Spring formation is similarly separated from the Archean by a thrust which intersects and offsets the thrust at the base of the Noonday dolomite. The Cambrian-Algonkian contact northwestward is offset by several northeasterly normal faults, successively down on the northwest; the largest of these is shown on Plate 2. They are analogous to the parallel large normal fault, or flaw, intersecting the same contact under the alluvium a quarter of a mile westward.

North of Tecopa a low-angle fault permits Wood Canyon formation to rest on Stirling quartzite and Wood Canyon formation. The shortest movement to such a position is westward. In view of thrusting 1½ miles southward, the low-angle fault north of Tecopa is probably a thrust. It is not certain whether the isolated Wood Canyon exposures at Tecopa are above or below this thrust.

The outcrop of Noonday dolomite south of Tecopa rests on a fault plane which dips at a low angle to the northeast. The Cambrian has ridden out over the Algonkian so as to eliminate the Beck Spring dolomite at two places and to leave only a thin slice of that formation elsewhere. That this is not due to unconformity is proved by the fact that the Cambrian dips at an angle of 55° into the pre-Cambrian. Half a mile northward a low-angle fault comparable to that north of Tecopa puts Stirling quartzite on Johnnie formation. That this is not normal superposition is indicated by the fact that the Johnnie strikes into the Stirling, whereas elsewhere in the area this contact is apparently comformable. (*See* Hazzard, 1937a, p. 305.) A quarter of a mile southwestward, the Johnnie and the Stirling are intimately mixed in what seems to be schuppen, apparently preserved from erosion after having been let down in a kind of graben. The schuppen may have developed adjacent to the low-angle fault described a quarter of a mile northeastward.

In the hills west of Shoshone a low-angle fault is generally present at or near the lower contact of the Bonanza King formation. In some places the Bonanza King rests on the Cadiz in seemingly normal superposition. But certain beds at the base of the calcareous series are not everywhere present, and along the strike the Bonanza King formation completely trangresses the Cadiz. The plane of division is not everywhere at the base of the Bonanza King; it is in some places down in the Cadiz. Where calcareous beds are on the fault plane, local brecciation has occurred. Where the fault plane is between the Cadiz and the Wood Canyon, a white rock flour developed. The exposure of the Wood Canyon surrounded by the Bonanza King on the east side of the hills is a fenster, and the exposures of the Wood Canyon and the Cadiz in the re-entrant at the south end of the hills, though not completely surrounded, are comparable. Two low-angle faults superposed on the west side of the re-entrant suggest imbrication. Incomplete exposures make the relation of the Wood Canyon to the surrounding Cadiz entirely doubtful. Just northward a small area of the Cornfield Springs of partly doubtful extension is quite close to the Bonanza King-Cadiz fault contact suggesting that the fault plane cuts high in the Bonanza

King section here and much lower east and west of this point, or, in other words, that the fault plane cuts across folded Cambrian sediments.

PROBLEMATICAL FAULTING

From the north side of the basalt mass near the area just discussed a fault emerges that dips 10° W. and separates the Bonanza King from the Cornfield Springs. The presence of the latter is confirmed by characteristic fossils. This low-angle fault probably intersects that on the west side of the hill separating Cadiz and Bonanza King formations from Wood Canyon formation. The two faults are connected in plan by a transverse normal fault, which apparently raised the north block sufficiently to eliminate the low-angle fault on the south. If the mapping is correct, the fault between the Wood Canyon and the Bonanza King allows for farther westward movement of the separated toe of the larger sheet. This continued movement may have been caused by gravity or by drag beneath an overriding mass. In view of the discommensurate displacements of the west-dipping low-angle fault and the westerly transverse fault, the low-angle faulting occurred before the final emplacement of the Bonanza King and associated strata on the Wood Canyon formation.

Low-angle faulting of similar plan is exposed half a mile northward. Here again the fault on the west side of the hill is offset eastward by an easterly transverse normal fault. On the south side of this transverse fault, a west-dipping low-angle normal fault branches off slightly eastward and passes underneath a mass of basalt. The pattern is the same as that in the faulting half a mile southward. In addition the window of the Wood Canyon adjoins, which does not require a different explanation. The inferred junction beneath the basalt of the low-angle fault with the fault plane between the Bonanza King and Wood Canyon formations is specified in the explanation of the faulting half a mile southward. We are probably dealing with a series of "inverse schuppen"—that is, minor slices tending to elongate a thrust, produced by drag transmitted downward from an overriding thrust plate. Whereas schuppen faults dip in the direction from which movement has occurred, these faults dip toward the direction of movement. This type of deformation is not paralleled by described examples from other localities.

STRUCTURAL DISCONTINUITIES

The compressive stresses have divided the sedimentary envelope in the Tecopa area on relatively horizontal planes. These tectonic unconformities are generally in one of three zones: (1) the lower part of the Crystal Spring, (2) the base of the Noonday dolomite, and (3) the base of the Bonanza King, or ranging from about the middle of the Cadiz up to several hundred feet above the base of the Bonanza King. The first is well developed south of the map area, where near the Western Talc Company mine the basal conglomerate of the Crystal Spring formation has been eliminated, permitting higher beds of the formation to rest on the Archean (personal communication from L. F. Noble). The plane at the top of the Archean is also favored by the Amargosa thrust, in the Virgin Spring area, west of the Tecopa area (Noble, 1941, p. 960).

The fault at the base of the Noonday dolomite is well exposed in the southern Nopah Range. The writer does not know where an undisturbed section of the Noonday dolomite might be found nor what might be the undisturbed basal relationship (unconformity, disconformity, or conformity). The lack of exposures revealing the Noonday in normal depositional contact with the older rocks, and the older rocks with the Archean, raises the question as to how far the younger rocks have moved horizontally in relation to the Archean basement below.

In the Johnnie area north of the Tecopa area Nolan has described the Johnnie formation-Stirling quartzite contact as the Johnnie thrust. As mentioned in the discussion of the stratigraphy of the Johnnie, in the Tecopa area the top has been mapped as conformable with the Stirling. The disconformity suggested by Hazzard at this horizon may indicate the presence of the Johnnie thrust or a correlative dislocation.

The base of the Bonanza King formation is extensively disturbed in the hills west of Shoshone by low-angle faulting. In the Restings Spring Range little disturbance other than strike faulting was noted. However, the brecciated character of the basal Bonanza King in the southern Nopah Range has been alluded to in the description of tectonic outliers in the Wood Canyon formation. Moreover, a view of the Nopah Range from the flanks of the Kingston Range 6 to 8 miles away reveals the elimination of the lowest beds of the Bonanza King in the pass 4 miles from the north edge of the map area. In the absence of klippen or other evidence on the displacement of the fault which might be inferred here and elsewhere in the area, no fault is mapped. However, the tectonic significance of the change from incompetent sand, shales, and thin-bedded limestones to massive limestones and dolomites is emphasized by the recurrence of these individually doubtful conditions.

HISTORICAL GEOLOGY

The earliest events within the Tecopa area are recorded in the Archean granite gneiss. Information on the Ep-Archean revolution or the Ep-Archean erosional plane is lacking. It probably may be assumed that the Archean granite (gneiss) intruded a body of rock that subsequently was completely eroded. Whether the foliation of the granite was formed during its emplacement, during a separate phase of the same diastrophic episode, or later is not known.

On an erosion surface cut on the Archean whose presence is deduced from the difference in metamorphism between the Archean and Algonkian, the thick Pahrump series of late pre-Cambrian sediments was deposited. Types of sediment (and associated basic intrusives, in neighboring areas) in the Pahrump series are paralleled by types in the Unkar and Chuar series of the Grand Canyon area. Whether these three series were deposited in one or in two basins is not certain. Locally, minor unconformities, if any, within the Pahrump series have not been established.

The great Cambrian system in the Nopah Range is a conformable sedimentary sequence, save possibly for a minor discontinuity at the base of the Stirling quartzite, discussed by Hazzard (1937a, p. 305). That this may be a significant boundary is suggested by the pre-Cambrian "aspect" of the Johnnie formation. Regional stratigraphic studies by Hazzard and the writer have revealed no evidence for stratigraphically higher unconformities within the Cambrian.

Several unconformities in the post-Cambrian Paleozoic sequence in the northern Nopah Range reflect only weak diastrophism (Hazzard, 1937a). Essentially, however, the deposition of calcareous sediments such as the Bonanza King and Cornfield Springs formations may have continued at intervals until the Carboniferous, and possibly until the Permian. Whether lower Mesozoic sediments were deposited in the Tecopa area is not known. As a result, the effect of a possible diastrophic stage at the end of the Paleozoic cannot be separately estimated. Between the Carboniferous and the Tertiary the older rocks were uplifted and partly eroded. This movement is vague and may have been cumulative. It is tentatively suggested that the east-going thrust on the east flank of the Nopah Range, which puts Cambrian on Carboniferous, is a Laramide fault and is the oldest fault in the area. Laramide east-going thrust faults are numerous 30 miles eastward, in the Spring Mountains (Longwell, 1926).

The definitely Tertiary history of the region began with extrusion and probably intrusion (Tm on Pl. 1), accompanied or closely followed by deposition of ash and debris in Miocene?-Pliocene? lake beds, by some normal faulting, and possibly by folding. After erosion, thrust plates carried Cambrian and Algonkian rocks westward over the Tertiary sediments south of Tecopa and interposed fingers of Cambrian in the Tertiary volcanics west of Shoshone. The thrusts and low-angle faults of younger onto older rocks were developed at about this time, under similar stresses. Transverse normal faults probably developed simultaneously with the low-angle faults, in part as flaws. They might however be due largely to the relaxation following the Pliocene compression.

On an erosion surface developed within the ranges after the normal faulting, lake beds (at China Ranch) and basalt were deposited. The final elevation of the range blocks and the depression of the valley blocks were accomplished by broad northwesterly warping of the very complex basement of these deposits. The flanks of the resulting anticlines were elongated by normal faults, called "Basin Range faults." The best example is that at the west foot of the Resting Springs Range (Pl. 2). The tendency toward uplift resulted in the Dublin Hills in a fault of very irregular plan within the hill mass. Longwell (1926, p. 579) mentioned the unknown faulting in the valley areas and concluded "that the intermont valleys in general mark wide belts of profound faulting."

After the ranges were thus blocked out, a Pleistocene lake occupied much of the intermont valley area. Lake deposition was followed (and perhaps accompanied) by the transport and deposition of great volumes of gravel. The lake established an outlet across the gravel ridge southward. Subsequent settling movements have caused minor faults and warpings in the lake deposits. The present alluvial cycle followed.

REGIONAL IMPLICATIONS

Fifteen miles east and southeast of the Tecopa area Hewett (1928) has described the Shadow Mountain thrust, a low-angle dislocation involving Miocene volcanics and sediments that moved eastward. The writer believes the movement was westward, based on what he thinks is the tectonic nature of the Cambrian-Archean contact and of the Bonanza King (=Goodsprings in part)-Cadiz (=Bright Angel in

part) contact on the west side of Mesquite Valley. He suggests that the resemblance of the structure in the Shadow Mountain thrust area and in the Tecopa area, with Cambrain thrust on Archean in the one area, and Cambrain and other rocks thrust westward onto the Archean, Algonkian, Cambrian, and Tertiary rocks in the other, is sufficient reason for withholding a definite conclusion as to the direction of movement.

The Spring Mountains structure, as described by Longwell, Nolan, and Glock, contrasts strongly with that of the Tecopa area. The intervening 30 miles of range north of the Tecopa area to Nolan's Johnnie area should be mapped before comparisons are made.

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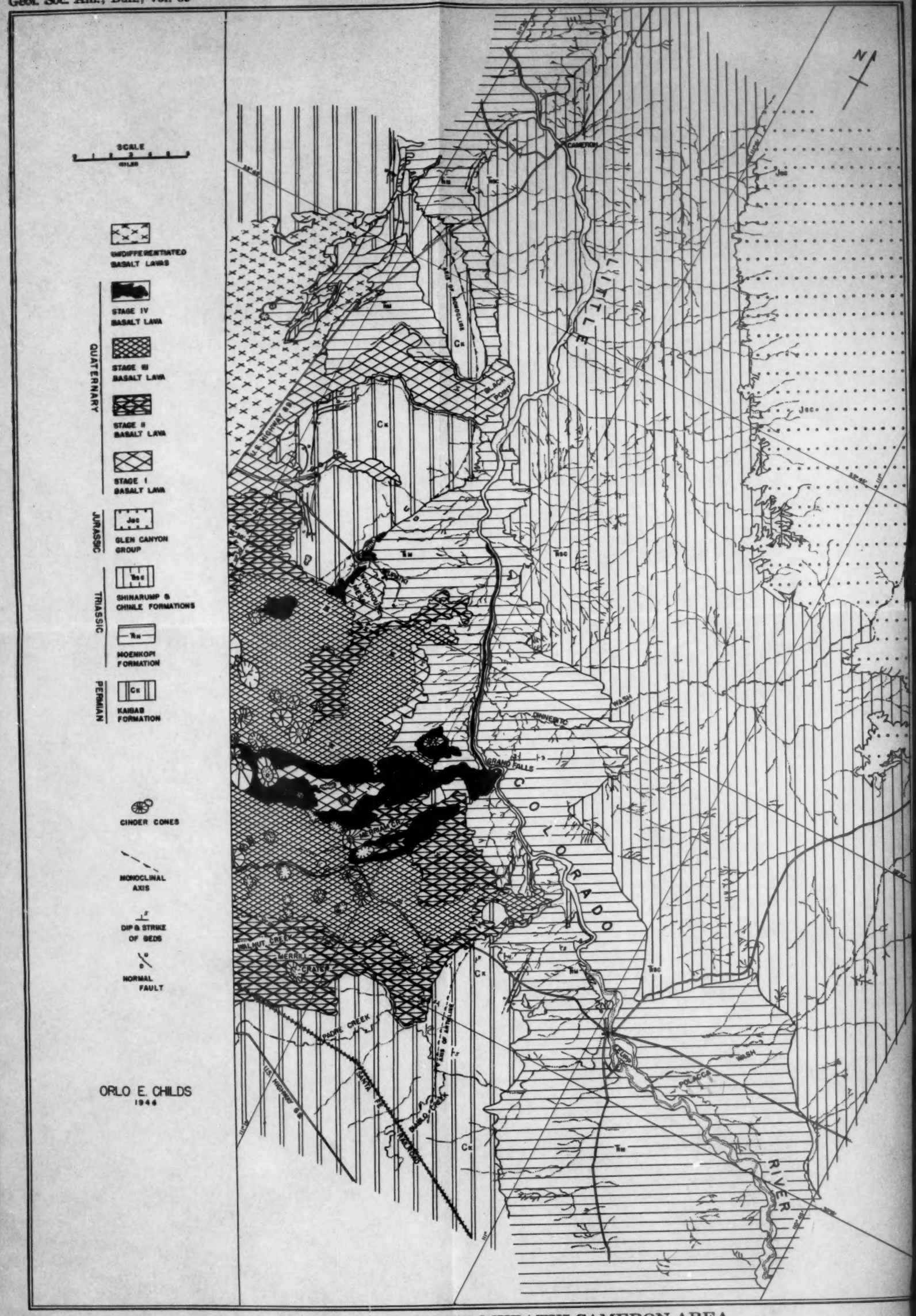


GEOLOGIC MAP OF LEUPP-WUPATKI-CAMERON AREA ALONG THE LITTLE COLORADO RIVER, ARIZONA

Pl. 1

EXPLANATION

QUATERNARY

- Qal — **Alluvium** *(Unconsolidated sand, gravel, and boulders)*

UNCONFORMITY

- Qg — **Gravels** *(Partly consolidated, showing dips)*

UNCONFORMITY

- Qlb — **Lake beds**

UNCONFORMITY

- Qb × — **Basalt flows** *(Relation to Qcr unknown)*
- Qcr — **China Ranch beds; lacustrine** *(Relation to Qb and Qlb unknown)*

TERTIARY

UNCONFORMITY

- Tm × — **Heterogeneous sediments of volcanic origin, including volcanic ejectamenta and lake beds**
- Tv × — **Volcanic rocks of various kinds, including flows and tuffs** *(Relation to Tm unknown)*

CARBONIFEROUS

UNCONFORMITY

- Cmc — **Monte Cristo (?) limestone** *(Mississippian)*

CAMBRIAN

UNCONFORMITY

- Ccs — **Cornfield Springs formation** *(Mostly dolomite; sand and shale at base)*
- Cbk — **Bonanza King formation** *(Mostly dolomite)*
- Cc — **Cadiz formation** *(Sandstone, shale, and limestone)*
- Cwc — **Wood Canyon formation** *(Sandstone and shale)*
- Cs — **Stirling quartzite**
- Cj — **Johnnie formation** *(Mostly sandstone)*
- Cn — **Noonday dolomite**

ALGONKIAN

UNCONFORMITY

- Kpn — **Kingston Peak formation** *(Shale and breccia)*
- Abs — **Beck Spring dolomite**
- Acs — **Crystal Spring formation** *(Quartzite and dolomite)*

ARCHEAN

UNCONFORMITY

- gneiss — **Granite gneiss**

× **Units of partly or entirely igneous origin**

Geologic boundaries, dashed where inferred

Fault showing dip of plane and (U) up and (D) down-thrown sides

Low angle fault, showing over-riding

Maintained road

Poor passable road

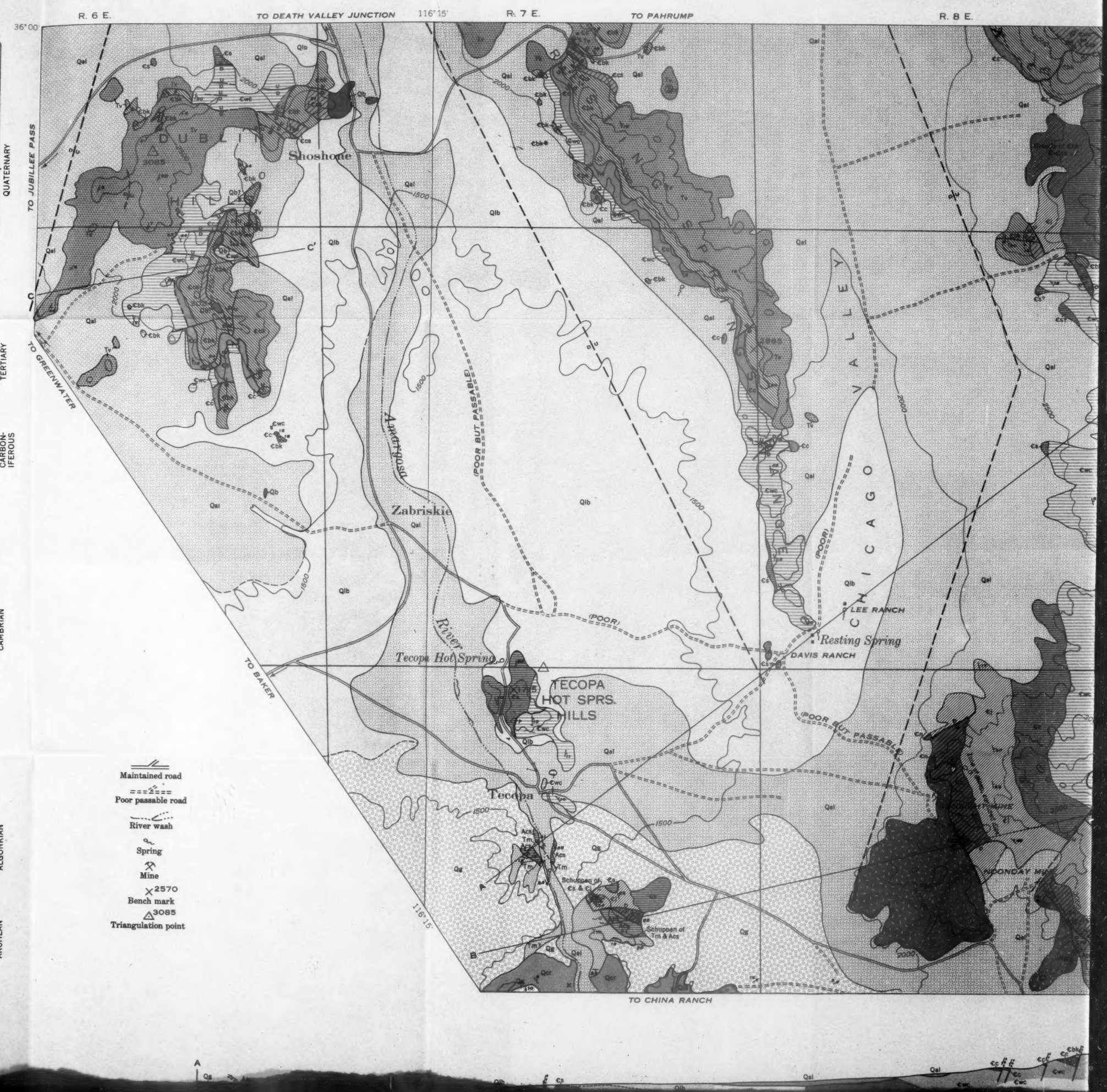
River wash

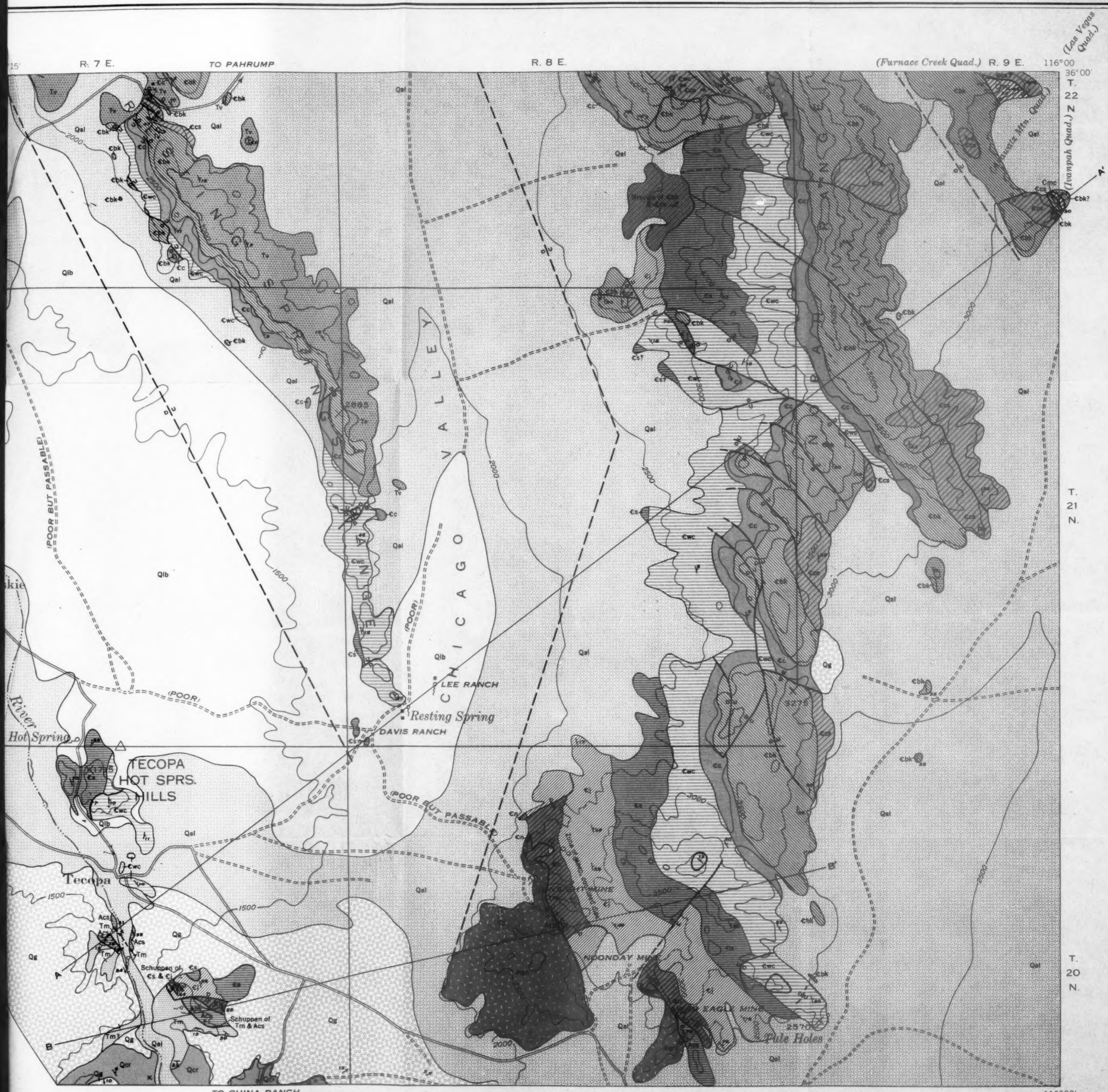
Spring

Mine

×2570 **Bench mark**

△3085 **Triangulation point**




R. 7 E.
TO PAHRUMP
R. 8 E.
(Furnace Creek Quad.) R. 9 E.
116°00
36°00'
(Las Vegas Quad.)
(Ivanpah Quad.)
T. 22 N
T. 21 N.
T. 20 N.
116°00'
TO CHINA RANCH
SPRING MTNS.
CHICAGO VALLEY
PANAMINT RANGE
Qal
Qlb
Tv
Tvs
Tvo
Tmc
Tm
Acs
Qg
Qcr
Ccs
Cwc
Cbk
Cc
Cs
Cmc
Cbk?
(POOR BUT PASSABLE)
(POOR)
LEE RANCH
Resting Spring
DAVIS RANCH
Hot Spring
TECOPA HOT SPRS. HILLS
Tecopa
Schuppen of Cs & Cl
Schuppen of Tm & Acs
Schuppen of Cbk
Trace of Panamint Thrust
MONDAY MINE
EAGLE MINE
Pule Holes
Quartz Mtn. Quad.
2000
2500
3000
3500
4000
1500
2885
3276
2570
A
A'
B
B'

Basalt flows
(Relation to Qcr unknown.)

China Ranch beds; lacustrine
(Relation to Qb and Qlb unknown.)

UNCONFORMITY

Heterogeneous sediments of volcanic origin, including volcanic ejectamenta and lake beds

Volcanic rocks of various kinds, including flows and tuffs
(Relation to Tm unknown.)

TERTIARY

UNCONFORMITY

Monte Cristo (?) limestone
(Mississippian)

CARBONIFEROUS

UNCONFORMITY

Cornfield Springs formation
(Mostly dolomite; sand and shale at base)

Bonanza King formation
(Mostly dolomite)

Cadiz formation
(Sandstone, shale, and limestone)

Wood Canyon formation
(Sandstone and shale)

Stirling quartzite

Johnnie formation
(Mostly sandstone)

Noonday dolomite

CAMBRIAN

UNCONFORMITY

Kingston Peak formation
(Shale and breccia)

Beck Spring dolomite

Crystal Spring formation
(Quartzite and dolomite)

ALGONKIAN

UNCONFORMITY

Granite gneiss

ARCHEAN

× Units of partly or entirely igneous origin

Geologic boundaries, dashed where inferred

Fault showing dip of plane and (U) up and (D) down-thrown sides

Low angle fault, showing over-riding block and dip of plane; (T) where interpreted as thrust fault

Inferred fault

Strike and dip of beds

Strike and dip of overturned beds

Prevailing dip of beds

A——A′ Line of cross-section

Maintained road

Poor passable road

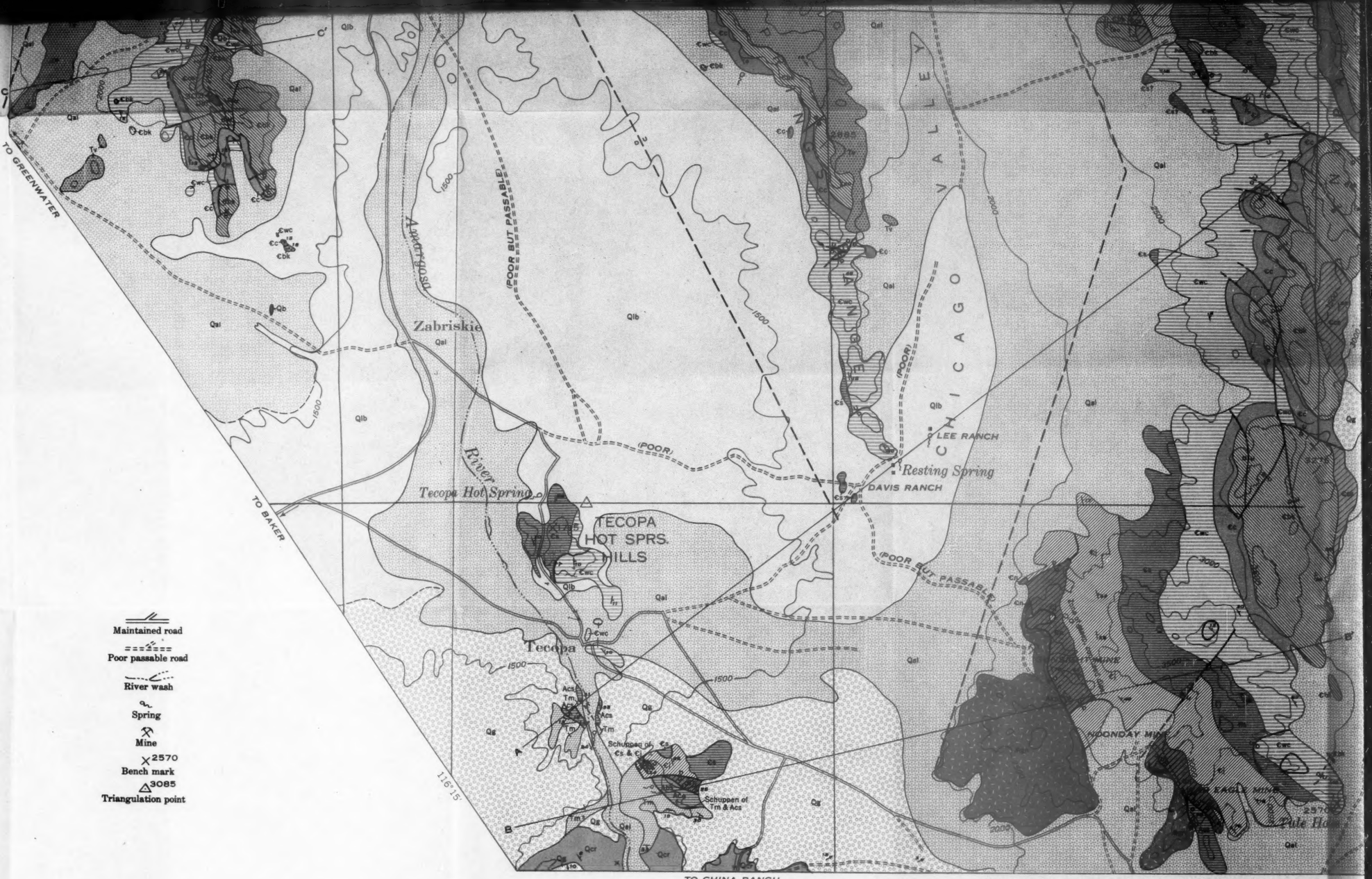
River wash

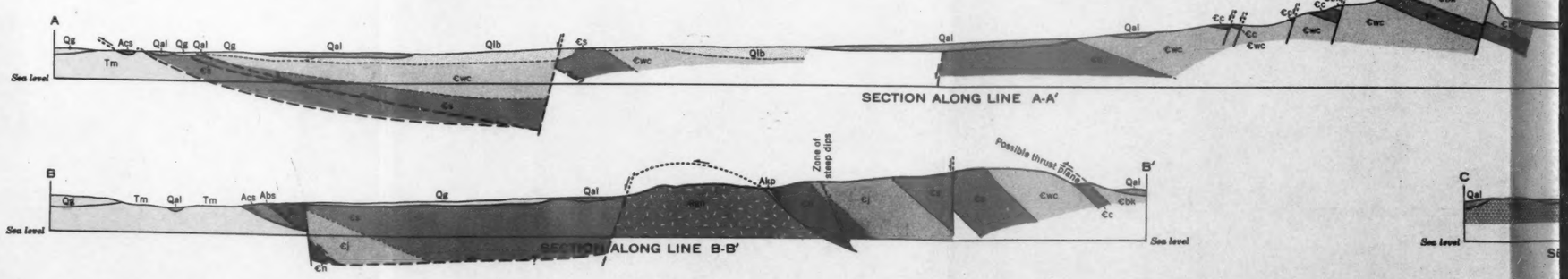
Spring

Mine

×2570 Bench mark

△3085 Triangulation point





Base from U. S. Geological Survey topographic map of Avawatz Mountains Quadrangle, Calif.

GEOLOGIC MAP AND SECTIONS OF THE TECOPA AREA, CALIFORNIA

Scale 1:62,500

0 1 2 3 4 5 Miles

(Horizontal and vertical scales equal)

Contour interval 500 feet

TERTIARY

CARBONIFEROUS

CAMBRIAN

ALGONKIAN

ARCHEAN

Maintained road

Poor passable road

River wash

Spring

Mine

×2570 Bench mark

△3085 Triangulation point

TO GREENWATER

TO BAKER

TO CHINA RANCH

Amargosa River

Zabriskie

Tecopa Hot Spring

TECOPA HOT SPRS. HILLS

Tecopa

Resting Spring

LEE RANCH

DAVIS RANCH

CHICAGO VALLEY

NOONDAY MINE

EAGLE MINE

Pule Holes

(POOR BUT PASSABLE)

(POOR)

Schuppen of Cs & Cj

Schuppen of Tm & Acs

T. 21 N.

T. 20 N.

116°15

116°00'

SECTION ALONG LINE A-A'

SECTION ALONG LINE B-B'

SECTION ALONG LINE C-C'

Sea level

Zone of steep dips

Possible thrust plane

Data projected along strike

GEOLOGIC MAP AND SECTIONS OF THE TECOPA AREA, CALIFORNIA

Scale 1:62,500

0 1 2 3 4 5 Miles

(Horizontal and vertical scales equal)

Contour interval 500 feet

Geology by John F. Mason, assisted by James B. Knight, Jr., Surveyed June, July 1940

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The area of detailed study is readily accessible from main highways. U. S. Highway 66, into Flagstaff, crosses the southwestern corner of the area and branch roads reach to the river downstream from Leupp at Grand Falls and pass through Leupp en route to the Hopi Villages in the highlands of Black Mesa. From Flagstaff to Cameron, U. S. Highway 89 crosses the northwestern corner of the area, and a branch road runs eastward to the Indian ruins at Wupatki National Monument and to the Little Colorado River.

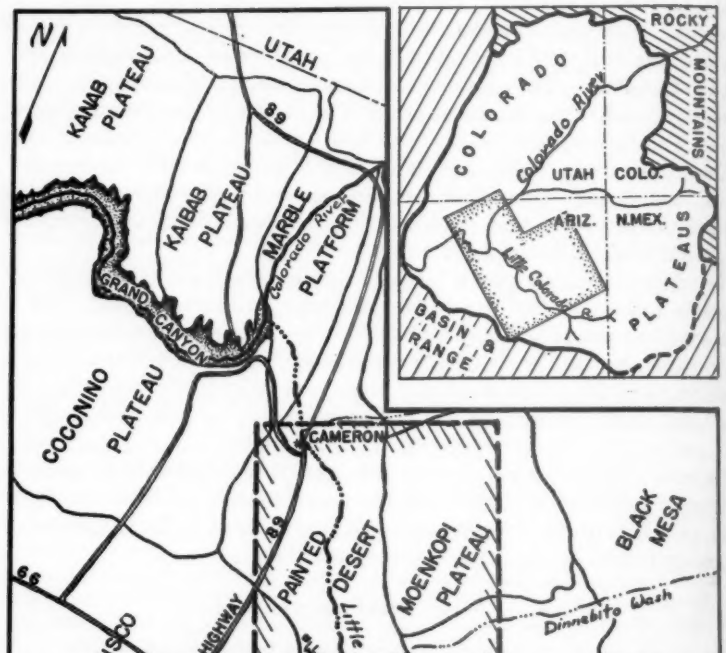

FIGURE 1.—*Index map*

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12,000 feet. Eastward from the river the surface rises gently to the foot of the colorful Chinle cliffs, then over a series of steplike cliffs to the distant plateau highlands of Black Mesa.

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BULLETIN OF THE GEOLOGICAL SOCIETY OF AMERICA
VOL. 59, PP. 353-388, 4 PLS., 7 FIGS. APRIL 1948

GEOMORPHOLOGY OF THE VALLEY OF THE LITTLE COLORADO RIVER, ARIZONA

BY ORLO E. CHILDS

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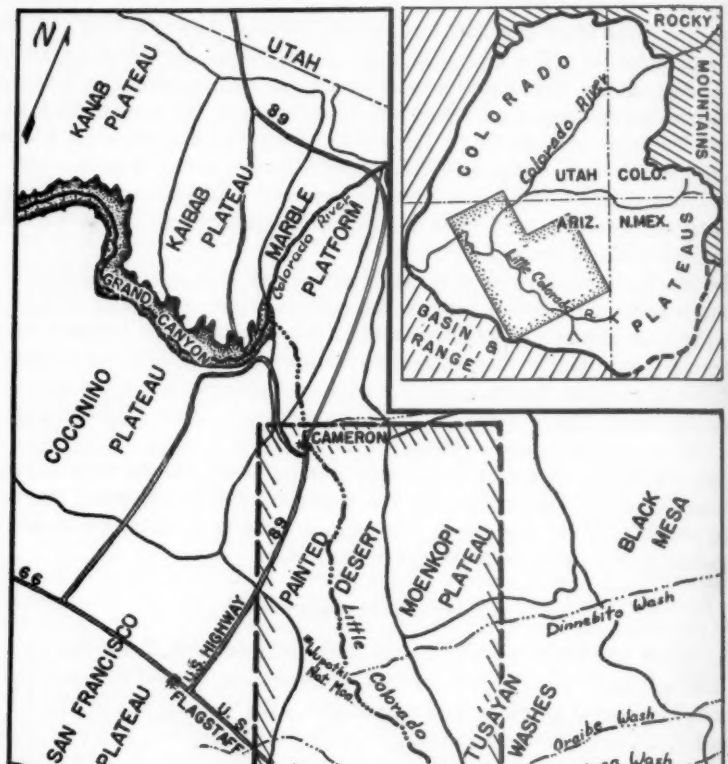

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occur aloft with the rain evaporating before reaching the ground. During the wet season intense storms may occur for short periods, and the dry washes suddenly become choked with muddy torrents. Only a relatively small increase in elevation provides a marked increase in rainfall and associated lower temperatures.

STRATIGRAPHY AND PETROLOGY

GENERAL CHARACTER AND DISTRIBUTION

The valley of the Little Colorado River from Leupp to Cameron exposes Permian, Triassic, Jurassic, and Late Tertiary rocks. The Permian layers are sandstones, cherty limestones, and dolomites of the Kaibab formation. The Triassic includes the red sandstones, shales, conglomerates, gypsum, and variegated shales of the Moenkopi, Shinarump, and Chinle formations. The Jurassic includes the massive sandstones, and shales of the Glen Canyon group. The late Tertiary rocks comprise a series of basaltic lavas in large part blanketed by an extensive covering of basaltic ash and cinders. Also, numerous deposits of well-rounded, weathered, and unconsolidated gravels cap remnants of pediments. The gravels are commonly 6 to 8 feet thick but in places reach 20 feet. They consist largely of the resistant types of rock of all the older formations.

In this region, as in most of the plateau country, the general horizontality of the beds, their deep dissection, and the sparsity of vegetation facilitate stratigraphic studies. Some of the earliest geologic work in the West included a general classification and dating of the section in the Little Colorado River Valley. In Ives's (1861) report, the valley of the Flax River (Little Colorado) was described, and the "Carboniferous" rocks with younger shales and marls were noted. Later brief visits by the geologists of the Wheeler Survey in 1875 added stratigraphic details. Since 1900 Ward (1901), Gregory (1917), McKee (1938), and others have studied the formations of the area in considerable detail.

A geologic map (Pl. 1) of the Leupp-Wupatki-Cameron area along the Little Colorado River was made by using the photographic mosaics of the Soil Conservation Service. Each controlled mosaic covers an area of 15 minutes of longitude and latitude at a scale of an inch to the mile. Sedimentary contacts and the limits of lava flows were located, examined in the field, and traced upon the mosaics. The area west of Longitude 111° 20′ W. was taken largely from a geologic map prepared in a similar manner by Babenroth and Strahler (1945). The region west of Long. 111° 20′ W. and south of Lat. 36° 25′ N. was adapted from a map drawn from aerial mosaics by H. S. Colton as a continuation of his work in Bulletin 10 of the Museum of Northern Arizona.

KAIBAB FORMATION

Gilbert (1875) included the Kaibab formation as the upper 200 to 220 feet of his Aubrey group. Darton (1910) subdivided the Aubrey group into three formations: the Kaibab limestone (including the present Kaibab and Toroweap), the Coconino sandstone, and the Supai formation (the present Hermit and Supai). Noble (1928) described a complete section of the Kaibab limestone in the deep canyon of Kaibab

Gulch. This tributary gorge runs into the Colorado River just north of the Arizona State line, and it is recognized today as the type section for the Kaibab formation.

Beds of the Permian Kaibab formation are extensively exposed along the western side of the Little Colorado Valley. Where erosion has cut through the resistant Kaibab, the valleys are gorge-shaped. Along the course of the Little Colorado, and to the west, local structures have so raised the Kaibab that nearly barren strip surfaces are particularly conspicuous. Farther west the Kaibab formation rises and forms the surface of the highest topographic elements of the region, namely, the San Francisco, the Coconino, and the Kaibab plateaus.

Downstream approximately 11 miles from Leupp, the Little Colorado enters a steep-walled canyon which continues for 16 miles to Black Falls. The abrupt walls reach a maximum height of 200 feet and expose a complete section of the Kaibab formation (Pl. 2, fig. 1). Beds of yellow to white limestone, and sandy limestone with nodules of chert occur from top to bottom, but half the total thickness is made up of calcareous yellow and red sandstone. The Kaibab rests on a white cross-bedded sandstone, 4 feet of which is exposed in the bottom of the gorge. McKee (1938) has divided the original Kaibab into the Kaibab (upper) and Toroweap (lower) formations. The lower 4 feet of white sandstone seen in the canyon at Grand Falls may be the top of the Toroweap. McKee believes that the Kaibab formation thins eastward from the Grand Canyon and is a near-shore facies along the Little Colorado River.

The Permian strata are the oldest exposed in the area of this study.

MOENKOPI FORMATION

The Moenkopi is the lowest of the thick Mesozoic formations that lie with hardly perceptible unconformity on the Kaibab. These Mesozoic strata were first studied by Ward (1901) who named them the "Moencopie beds", and recognized that they lie unconformably on the "Carboniferous Upper Aubrey" (Kaibab). In later regional studies Gregory (1913; 1917) identified the age as Permian, based on fossils found and identified by Walcott from the Kanab Valley, Utah. More recently, Baker and Reeside (1929), have reported the Moenkopi formation as Lower Triassic, and at least in part of marine origin. It is so held by most of the present workers in the area.

In the area of this study, the section of red sandstones and shales of the Moenkopi formation is best seen west of the river. The Little Colorado River is bedded in the Moenkopi, for the most part midway between the lower and upper contacts. Along the western side of the river the Moenkopi is much dissected, and the contact with the underlying Kaibab is very irregular. Here, the Moenkopi makes up numerous island like erosion remnants that are wasting away rapidly on a floor of resistant Kaibab.

In the sections measured, the Moenkopi formation ranges in thickness from 336 to 350 feet. The base of the formation contains a few lenticular conglomerates of limestone, chert, and sandy limestone. Proceeding upward in the section there are: an interbedded series of red shale and thin limestone beds, red and white shale with selenite layers, finely laminated white shale and red shale, and massive red sandstone

and shale layers replete with ripple marks and mud cracks. An uppermost zone of 22 feet is remarkably persistent. It is made up of two members—a fissile red shale criss-crossed with calcite veins, and a massive, cross-bedded, red sandstone.

SHINARUMP AND CHINLE FORMATIONS

Gilbert (1875) named the Shinarump conglomerate and dated it as Triassic. Gregory (1913) pointed out its persistent character over large areas throughout the Colorado Plateau province in Utah, Arizona, and New Mexico. The thickness ranges from 20 to 382 feet, but over large areas it is somewhat less than 100 feet. He considered it to be the base of the Triassic system, since he considered the underlying Moenkopi to be Permian. He recognized a slight unconformity at the base of the Shinarump but found the bedding conformable upward into the overlying shales and marls of the Chinle formation.

Today, the Moenkopi is considered Lower Triassic, the Shinarump is held as Upper (?) Triassic and at the base of the undoubted Upper Triassic beds of the Chinle (Gregory, 1917). Its type locality is in the Shinarump cliffs south of the Vermillion cliffs in Kane County, Utah.

Along the eastern side of the valley of the Little Colorado the Shinarump conglomerate is only 26 to 50 feet thick and commonly forms a resistant cap rock of cuestas. Usually the base of the cuesta is of Moenkopi, and, as at Black Falls, the crest is 150 to 200 feet above the river. Locally, there is some variation in the size of pebbles of the conglomerate and in the strength and degree of cementation. This results in an irregular resistance to erosion and renders variable the cliff-forming habit of the formation.

The usual lithology includes a lower zone of red cross-bedded sandstone with chert pebbles nearly an inch in diameter, and with clusters of black ferruginous concretions. Above these beds are fine-grained, white, cross-bedded sandstones and coarse red sandstones with bean-sized black concretions.

The Chinle formation of Upper Triassic age was originally described by H. E. Gregory (1916) from the Chinle Valley of northeastern Arizona. The formation varies in thickness from 400 to 1000 feet throughout the Colorado plateaus. Details of its lithology and stratigraphy have been described by many workers in the Plateau Province.

The brilliantly colored beds of the Chinle may be seen along the eastern flank of the Little Colorado River Valley making up the steep west-facing front of a long, somewhat continuous cuesta ridge. The layers of variegated shales with only a few resistant beds have made the formation weakly resistant to erosion. Hence, the retreating cuesta front stands at the head of a long well-developed pediment that slopes gently toward the Little Colorado. The Chinle formation in this region ranges from 500 to 575 feet in thickness and consists of a lower group of beds approximately 200 feet thick that predominate in shales with colors of buff, gray, blue, chocolate, red, purple, and white. There is a central zone, 50 feet thick, of sandstone and conglomerate made up of buff and gray sand rich with inclusions of chert and quartzite pebbles, as well as numerous fragments of petrified logs. The upper group of

strata, 300 feet or more thick, exhibits a greater number of limestone, bedded chert, conglomerate, and sandstone beds interlayered with shale, the predominant rock. The numerous resistant beds in the upper part of the formation commonly make cliffs in this part of the section. In the upper zone the colors continue to vary through gray, buff, red, purple, blue, and white.

The top of the Chinle formation contains beds of red sandstone and shale more thinly bedded, and usually of finer texture than the massive overlying formations of the Glen Canyon group. In the area of this study, the contact with the Glen Canyon seems conformable, but Gregory (1917) concludes from his studies in other areas that there is ample evidence to indicate not only a break in sedimentation, but an erosional interval.

GLEN CANYON GROUP

The Glen Canyon group includes the Wingate sandstone, the Kayenta formation (originally the Todilto sandstone), and the Navajo formation. It is considered to be Lower Jurassic (?). The Wingate formation appears as a massive red sandstone cliff east of the Little Colorado River. The escarpment is 16 miles northeast of Leupp and 9 miles east of the river at Cameron. The massive cliff-making formations of the Glen Canyon group stand as steplike benches that extend far back into the eastern drainage area of the Little Colorado.

BASALTIC LAVA FLOWS

Character and distribution.—Basaltic lava flows of the eastern and northeastern periphery of the San Francisco volcanic field extend into the region immediately west of the Little Colorado River. Here they are associated with erosional features and may be related to the sequence of geomorphic events.

Robinson (1913) established three general periods of volcanic activity in the San Francisco volcanic field. The first, in late Pliocene, was characterized by widespread eruptions of thin basalt flows largely from local vents and in part from fissures. During the second more intense period, approximately 56 cubic miles of lavas was erupted, ranging from andesite to rhyolite, and laccoliths were intruded. During this second period such high topographic features as the San Francisco Peaks and Sitgreaves, Kendrick, and Bill Williams peaks were formed. Most of the peaks are made up of two or more types of lavas ranging from acidic to intermediate in composition. The third period was again one of basaltic extrusion. The lava this time was somewhat more viscous than that of the first period and the flows are thick and of lesser extent. Two hundred or more basaltic cinder cones were formed with a somewhat uniform distribution over the whole volcanic field, except east of the San Francisco peaks where they are particularly abundant.

Robinson's (1913) first and third period lavas include all the basaltic flows along the western flank of the valley of the Little Colorado. His chemical analysis and studies of numerous thin sections showed a "decidedly uniform mineral composition . . . an equally uniform chemical composition" of first and third period basalts. All the lavas in the area of the present study were strikingly similar megascopically

and seem to emphasize Robinson's (1913) statement that "each period (first and third) is represented by a single lava—a typical basalt—of uniform composition."

Colton (1937) developed a useful chronologic classification of basaltic flows and cinder cones in the San Francisco area based on the degree of weathering and erosion. The determination of the relative age of flows is not always easy. The older flows cannot be traced any great distance. Locally they are covered by cinder deposits or are hidden beneath younger lavas. Only the youngest flows can be traced with confidence. In some places old flows stand isolated as the resistant caps of mesas. Young flows in some places reach beyond the limits of older ones and spread over sedimentary layers at a lower level than the old lavas. Neither megascopically nor microscopically have the successive flows of basalt shown characterizing differences. Stratigraphic position and elevation of the flows must be considered with caution, and chief reliance for age determination must be placed on the relative amounts of weathering and erosion of the lavas, and of the surfaces over which the lavas flowed.

Colton's (1937) work was primarily directed toward greater detail regarding the cinder cones and lava flows of Robinson's third period of volcanic activity. He mapped the distribution of 388 cones and the outlines of lava flows. Characteristic criteria were set up for each of five stages of cones and flows. Since the successive age relationships are best shown on the northern and eastern periphery of the lava field, it is in this area that Colton's five stages are described.

The correlation chart (Table 1) illustrates the relationship of Robinson's (1913) lavas of the San Francisco field, the peripheral stages recognized by Colton, and the stages recognized in the area of this report.

Stages 1 and 2.—The basaltic lavas of Stages 1 and 2 have been subjected to a long period of weathering and erosion and look much older than the later lavas. The original extent of the flows cannot be recognized due to the erosional retreat of the edges, and through weathering the original lava surface is nearly gone. Aa and pahoehoe textural structures, as well as buckled pressure ridges and spatter cones, are all but lost on the relatively smooth surfaces of both Stage 1 and Stage 2 lavas.

Colton (1937) believes that Stage 2 flows show (1) relatively more traces of pressure ridges and spatter cones, and (2) evidence of deeper erosion of the floor over which the lavas spread. These features, together with superposition of Stage 2 lavas on Stage 1 wherever it could be demonstrated, were used in classifying the flows.

Age differentiation of lavas in the area of this study can be made with even more assurance. A sequence of pediments exists along the Little Colorado River and the different ages of the surfaces over which the lavas flowed provide a most satisfactory basis for separating Stage 1 from Stage 2. Stage 1 lavas are on the highest and oldest pediment where they have preserved an erosion surface that truncates shale and sandstone beds. Stage 2 lavas are found locally on a younger and lower pediment surface. The basaltic lavas of both stages have been so weathered and eroded that the original surface structures are nearly lost. The position of lava flows on erosion surfaces of different age further indicates a long interval or erosion between the two periods of extrusion. Since the lava flows of Stages 1 and 2 are often masked by cinders or younger flows, the relation to successive pediments is very helpful.

Stage 3.—Spatter cones and buckled pressure ridges, although somewhat subdued by weathering, identify Stage 3 lavas readily. The flows of Stage 3 are quite widespread and characteristically are 60 to 90 feet thick—much thicker than the older and younger flows. The fronts of the flows are serrate due to the headward extension of numerous gullies.

TABLE 1.—*Correlation chart of the San Francisco lavas*

Colton (1937)	Robinson (1913)	Present Paper	
Erosion 5th State	Erosion 3d period. Volcanic activity intermittently during uplift and "canyon cycle" of erosion	Erosion 4th Stage	Present
4th Stage		Erosion	
3d Stage		3d Stage	
2d Stage*	2d period of volcanic activity; occurred during wide-spread stripping and erosion. (acid lavas and intrusions)	Erosion	Pleistocene
		2d Stage	
1st Stage	Erosion	Erosion	
	1st period of volcanic activity	1st Stage	Late Pliocene
	"Great denudation"	Erosion	

*It is not clear whether Colton's second stage lavas were formed prior to Robinson's second period (acidic lavas) or subsequent to them.

Colton recognizes periods of time between his lava stages, but since he presents no chart of this type, no attempt is made here to represent those intervals.

The surface of the lava is still rather rough, although the scoriaceous structure is largely obliterated by weathering. An indication of the recency of these lavas with reference to the present topography is well shown 9 miles northwest of Leupp. Here a Stage 3 flow followed down through a steep-walled canyon and nearly reached the Little Colorado River. The tributary was cut down into the resistant Kaibab formation, and thus the lava flow follows a stream channel that was entrenched as a result of the last rejuvenation of drainage.

Stage 4.—The Stage 4 lavas are very fresh looking. Lava surfaces are extremely rough and very little affected by weathering. Common features are fresh spatter cones, buckled pressure ridges, and "cock's combs" where lava has squeezed up

through cracks like heavy grease. Very little or no gullying has developed around the edges of the flows. Where the flows extend beyond the limits of older lavas, they seek out the drainage channels leading to the Little Colorado.

In a flow of this stage at Grand Falls, the lavas found the river flowing in a rather narrow canyon some 200 feet deep (Pl. 2, figs. 1, 2). A thick lava dam was formed, and a flow 10 to 15 feet thick continued down the Little Colorado floor for 12 miles. For the most part the floor of the present channel is only slightly lower than the one over which the lava flowed, and the recency of the lava in the history of the river can be readily appreciated.

Colton (1937) has described a very recent Stage 5 lava associated with Sunset Crater, 20 miles west of the area of this study, approaching the San Francisco Peaks. These last flows are dated by archeological evidence as having occurred about 875 A.D.

CINDER CONES AND OTHER DEPOSITS

The San Francisco volcanic field contains a great number of volcanic cones. Many of the smaller cones, composed mainly of basaltic cinders, lapilli, and bombs, reach a height of 1000 feet. Cinder cones are particularly well developed in the eastern part of the field and are found in all stages of preservation. To Colton the amount of erosion and weathering of the cones is a key to a general classification and a suggested correlation with the successive lava stages. The correlation is most reliable in stages 4 and 5 because some of the lava flows can be traced to their source at the base of a cone.

The effect of wind on cinder cones and cinder-sand dunes is evident in many places. The prevailing wind direction is from the southwest to the northeast, and a resultant elongation is expressed in the cinder-cone profiles and in the position of dunes. An example of the effect of wind upon crater shape is seen at Merriam Crater (Pl. 1). Along a southwest-northeast cross section this great cinder cone is decidedly asymmetrical. The windward slope is very steep, approaching the angle of repose. The rim of the funnel-shaped crater at the crest of the cone is highest on the northeast side, and the leeward slope of the cone is inclined gently to the northeast.

Northeast edges of table lands are the sites for the accumulation of thick cinder deposits that slope downward steeply from the edge of the mesa. Ledges that face into the wind often have material deposited in front of them until slopes are formed up which the wind can roll cinders onto the highland beyond. These interesting fixed dunes usually form a segment of a cone with the apex in a notch in the ledge. The cinder deposit on the leeward side of the ledge has a steeper slope and is a more common deposit. Cinder deposits are found over lava flows of all stages, often masking the lava under a cover that tends to maintain a flat uniform surface over an irregular floor. The effect of such a porous cover greatly limits the amount of stream runoff; therefore, the headward growth of the gullies into the edges of lava flows, and into pediments so protected, is very slow. Below an elevation of 5500 feet vegetation becomes rather sparse, and wind transportation is most active. Above that elevation an increasing vegetation cover limits more and more the effectiveness of the wind.

FIGURE 1.

LOOKING NORTHWARD DOWNSTREAM FROM LAVA DAM AT GRAND FALLS

The river enters from the right and plunges over falls. Beds are Kaibab, lava in the foreground and to the left.

FIGURE 2.

LOOKING SOUTHWARD UPSTREAM FROM GRAND FALLS

Sediment-filled canyon behind lava dam. Note cinders in the foreground and along the (leeward) west canyon wall in the background.

FIGURE 1.
LOOKING NORTHWARD FROM SUMMIT OF MERRIAM CRATER
1. Stage 1 lavas capping a remnant of the Black Point pediplane, 2. Part of the Wupatki pediplane, 3. Stage 3 lavas, 4. Black Point, 5. Coconino Point and the Coconino plateau.

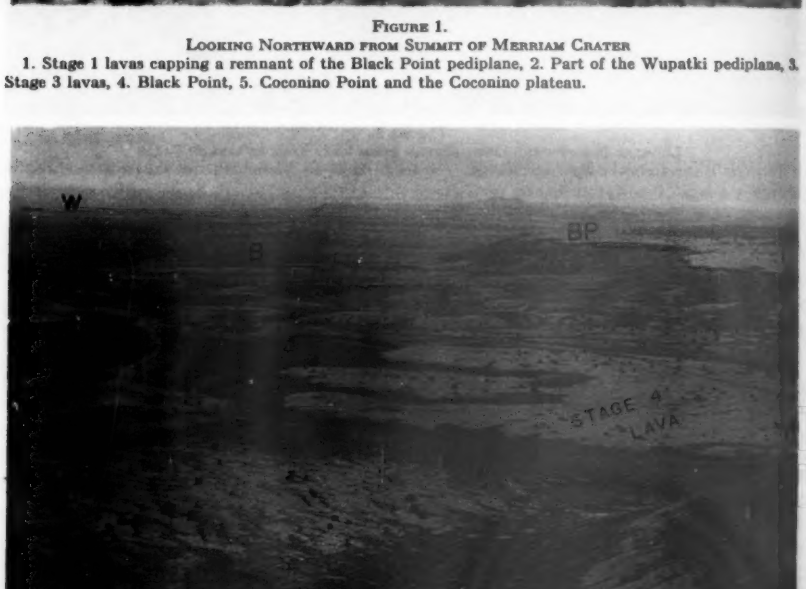

FIGURE 2.
VIEW IS EASTWARD FROM DONEY CRATER
W, Wupatki pediplane beneath Stage 2 lavas; BP, Woodhouse Mesa remnant of Black Point pediplane under Stage 1 lava; B, Interfluve remnants of the Wupatki "B" pediplane.

GEOLOGIC STRUCTURES

GENERAL CHARACTERISTICS

Nearly horizontal beds over large areas with local high-angle faults, sharp monoclines, and anticlines characterize the Colorado Plateaus. Most of the faults and folds of the province fall into two general age groups. Laramide structures include the broad domes, basins, sharp monoclines, and the anticlines of the eastern part of the province. The great high-angle faults, mainly in the western part of the province, occurred in the middle and late Tertiary.

The principal structural features east and southeast of Grand Canyon are represented in Figure 2. The East Kaibab monocline and its branches make up the dominant structure of the region, and to the east is the less imposing Echo monocline. East of the San Francisco Plateau a local reversal of dip results in the gentle Tolchaco anticline.

WESTERN PLATEAUS

The San Francisco, Coconino, and Kaibab plateaus extend along the western margin of the valley of the Little Colorado River and continue north and south well beyond it. The Kaibab formation forms the surface of the plateaus where it is 2000 to 3000 feet above its position at the river (Fig. 2).

The San Francisco Plateau is a great flat-topped structural dome crowned with volcanic cones and lava flows. U. S. Highway 66 ascends to the summit of this plateau in approaching Flagstaff from the east. In 30 miles the Kaibab formation rises steadily 2000 feet to the top of the plateau. Farther north along the eastern flank the plateau is buried beneath lavas and cinder cones. In front of the lavas the beds are arched up gently to form the Tolchaco anticline. Still farther north he Mesa Butte and Black Point monoclines emerge from beneath the lava cover. The summit of the plateau on sedimentary rocks is approximately 6800 feet above sea level. Here the Kaibab formation is the floor on which the Tertiary volcanics accumulated. However, at the town of Flagstaff, Moenkopi beds are exposed beneath the lava capping. The Kaibab beds dip gently to the north from the plateau summit, giving the northern and northeastern section a gentle domelike structure steepened locally by marginal folds.

The Coconino Plateau is that part of the nearly flat highland bordered on the north by the Grand Canyon and on the east by the East Kaibab monocline. From the rim of Grand Canyon at 7000 feet, the beds and the plateau surface are inclined southward at about 100 feet per mile. To the south this inclination gradually flattens and is reversed as the beds ascend toward the San Francisco Plateau. Thus, there is developed a broad saddle, hardly preceptible to the eye except as a skyline profile and best shown by drainage channels. The northeastern corner of the Coconino Plateau is depressed 600 feet below the general surface by the Grand View monocline, where it branches northwestward from the East Kaibab monocline and reaches across the corner of the plateau into the Grand Canyon. This depressed area is called the Upper Basin and is bordered by the Grand Canyon on the north,

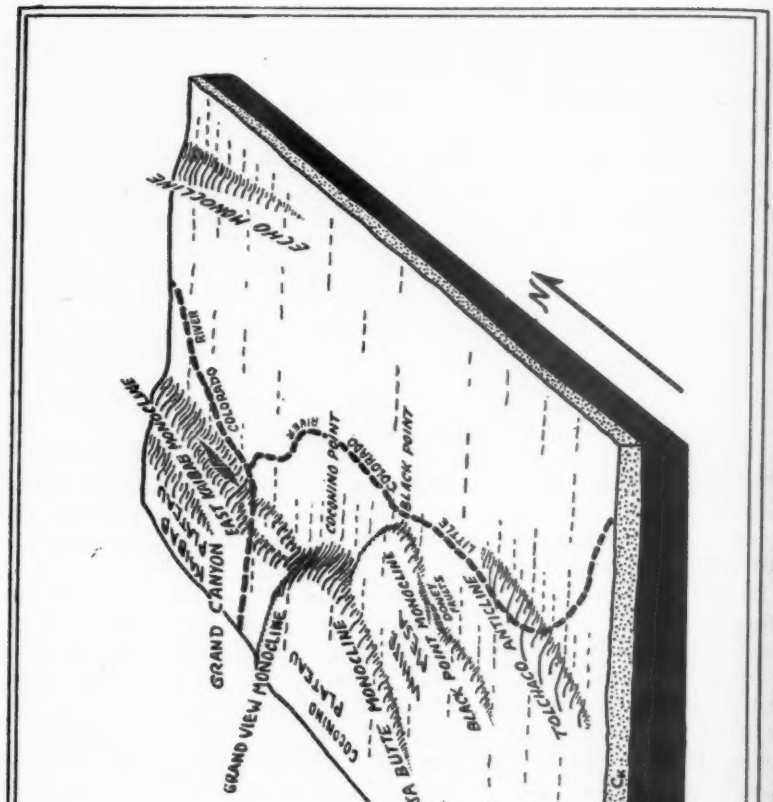

FIGURE 2.—*Diagram of regional structural features*

the Grand View monocline on the west and south, and the East Kaibab monocline on the east.

The highland north of Grand Canyon is the Kaibab Plateau, bordered on the east by the East Kaibab monocline. The Kaibab is the highest and easternmost of the group of plateaus through which the Colorado River has carved out the Grand Canyon. The general structure of the Kaibab Plateau is that of an elliptical dome with the long axis trending north. The Kaibab formation forms the surface of the plateau, and the beds continue in the same attitude as in the Coconino Plateau across the canyon. Northward from the North Rim of Grand Canyon the beds and the plateau surface rise 100 feet to the mile, from 8000 feet elevation over the flat crest of the dome at 9000 feet. Opposite this highest portion of the plateau the beds descend to the east over a double monocline fold.

MONOCLINES

The dominant structure of the region is the East Kaibab monocline. Sections of this great flexure have been described as parts of numerous regional studies in the plateau province. It was named by Powell (1875). Recently, Babenroth and Strahler (1945) have studied it as a structural unit and have described it in detail from the southern terminus under the San Francisco lavas to its northern end east of Bryce Canyon, Utah. Throughout this general north-south trend of 150 miles it is downthrown to the east reaching a maximum of 5000 feet.

The monocline is doubled along the eastern flank of the Kaibab Plateau, and the beds descend 3000 feet in two steps from the top of the plateau to the Marble Platform. Opposite the junction of the Little Colorado and the Colorado rivers, and north of the Grand Canyon proper, the monocline becomes in part a fault whose displacement is 2000 feet. Additional drag gives a total displacement of 2700 feet. This is the Butte fault, and it represents a section of the monocline that has broken. However, to the north and south the fault gives way to a true monocline fold. The fault is approximately 15 miles long.

FIGURE 2.—*Diagram of regional structural features*

South of Grand Canyon the East Kaibab monocline consists of four distinct branches radiating from the highest point in the region, Coconino Point. Here the displacement due to the fold reaches a maximum of 2300 feet in a horizontal distance of a mile. Babenroth and Strahler (1945) point out a fault midway on the monocline limb, with its strike following that of the fold as it swings around Coconino Point. Throw of the fault is opposite the displacement of the fold and reaches a maximum of 200 to 300 feet. Northwestward 6 miles from Coconino Point the displacement along the monocline decreases to 1200 feet. Here, the fold divides into two branches of equal throw, which trend nearly at right angles to each other. One branch swings to the west, and the other to the north (Fig. 2). The west branch is the Grand View monocline which continues westward 6 miles, then northwestward into the Grand Canyon where it dies out. The branch that runs northward becomes a double monocline for a short distance. The displacement is increased to 900 feet at Grand Canyon and continues northward as the section of the East Kaibab fold already described. Southward from Coconino Point the

displacement of the monocline decreases to 1500 feet where it branches again nearly at right angles (Fig. 2). The Mesa Butte monocline continues to the southwest, decreasing in throw gradually from a maximum of 750 feet. It dies out east of the saddle between the Coconino and the San Francisco plateaus. The Black Point monocline is a very gentle fold at its junction with the more abrupt Mesa Butte branch, but to the southeast the dip reaches 20°, and the displacement increases from 600 to 1000 feet just north of Black Point. The fold swings around Black Point changing its trend to southwest. Five miles southwest of Black Point the steep monoclinal fold breaks into a fault which continues for 3 miles until it disappears beneath the lavas and cinder cones of Doney crater. Beyond the crater to the southwest, the monocline continues 2½ miles before disappearing beneath the San Francisco lava flows.

Babenroth and Strahler (1945) believe that the East Kaibab monocline was probably produced in a single period of flexing of Laramide or early Tertiary date. This age is shown clearly in the area of Canaan Peak, Utah, near the northern end of the fold, where Eocene beds lie unconformably on folded Cretaceous beds. However, stratigraphic evidence is lacking for dating of deformation along the middle and southern parts of the monocline.

The Echo Cliffs face westward across the Marble Platform opposite the Kaibab Plateau. The west-facing escarpment is cut in Mesozoic rocks and stands near the axis of a monocline which folds the beds down to the east. Thus, the topographic expression of this monocline is exactly opposite to that of the East Kaibab monocline. The Echo monocline has much less displacement than does the Kaibab to the west, and it dies out north of the Little Colorado River.

TOLCHACO ANTICLINE

The Tolchaco anticline is a low, gentle fold extending northeastward from U. S. Highway 66 to Dinnebito Wash (Pl. 1). It is asymmetrical at its southern end but becomes more symmetrical to the north. The axis of the fold trends north-northeast throughout most of its 24-mile length. Northeast of the Santa Fe Railroad crossing of Diablo Creek, the Kaibab beds at the surface lose their regional dip as the fold takes form. Diablo Creek crosses the axis where the fold is not pronounced and continues parallel with the axis of the fold to the junction with Padre Creek. Padre Creek approaches the fold from the west, flows southwestward across the axis and eastward to the junction with Diablo Creek. The western limb dips 10°, and the eastern limb 5°. The maximum structural relief of the fold is approximately 200 feet. To the north the slightly asymmetrical character is not pronounced as the fold continues obliquely across the path of the Little Colorado River. Downstream from the old mission site of Tolchaco the Little Colorado enters a canyon zone where the anticline raises the top of the Kaibab formation above the gradient of the river. This canyon zone continues for 16 miles across the fold at a very small angle to the axis. Evidence of the fold is lost north of Dinnebito Wash where the beds resume their eastward regional dip of 3°. Closure, if it exists at all in the Tolchaco anticline, is less than 100 feet.

GRABENS

Apart from the faulted monoclinal limbs numerous single faults and elongated graben trenches have been mapped. Babenroth and Strahler (1945) show 24 grabens resulting along faults with marked displacement. The grabens shown by these authors occur mostly on the Coconino Plateau, along the Little Colorado River east and northeast of Coconino Point, and on White Mesa. The displacements are of the order of 100 feet, and a maximum of 200 feet is recorded. Babenroth and Strahler (1945) call attention to the pre-lava age of most of the faults and suggest that some of the structures were resequent grabens bordered by fault-line scarps and that the grabens show a regional alignment closely related to that of the folds. On the basis of these features a rather ancient faulting is implied.

Many such grabens may be buried by the lavas south of the region where they are now seen so clearly. Beyond the limit of the lavas, 6 miles west of Leupp, a rather small graben can be seen. The faults trend north, and the displacement amounts to only 12 feet.

GEOMORPHOLOGY

EROSION SURFACES OF THE LITTLE COLORADO

Statement of the problem.—The geomorphic problem is one of erosion. The most obvious conclusion is that flat and gently inclined beds of variable resistance and the activity of the master stream, the Little Colorado River, control erosion. Truncated beds, low cuestas, and strip slopes are features of the extensive lowland which in places stretches to cliffs on the distant horizon. Plate 3 gives a limited, though characteristic, view of the erosion surfaces.

The main object of the present study is to relate the erosion surfaces to structure, to distinguish interrupted cycles of erosion or multiple surfaces if they exist, to determine their ages and their relationships to the San Francisco volcanics, and to determine if local crustal movements have occurred during the development of the surfaces. Several distinct erosion surfaces were recognized, and their distribution was charted (Pl. 4). This map should be compared with the geologic map of the same area (Pl. 1) for the relation of erosional surfaces to the different formations and to structure.

During the past 20 years many geologists have paid particular attention to the broad plains of erosion that extend out from the abrupt fronts of mountains in arid regions. The carved plain surfaces have been called "pediments", and the term has become well established in geologic literature. The erosion surfaces in the valley of the Little Colorado are characteristic pediments, and, as surfaces that have formed across sedimentary beds of different inclination and of different resistance to erosion, they are pediments with special characteristics. It is therefore necessary to review briefly the concept of pediments before treating the distinguishing features of those of the valley of the Little Colorado.

Erosion surfaces and the concept of pediments.—Pediments are gently inclined

planate erosion surfaces carved in bedrock and generally veneered with fluvial gravels. They have been widely recognized in arid regions (Bryan, 1925; 1933; Blackwelder, 1931; Johnson, 1932; Gilluly, 1937; Howard, 1942). Pediments occur between mountain fronts and valley or basin bottoms (Fig. 3) and commonly form extensive bedrock surfaces over which the erosion products from the retreating mountain fronts are transported to the basins. Slope is greatest near the mountain front, where gradients may be 300 to 500 feet per mile. Valleyward, the slope becomes sensibly flat, although the gradients may actually be 20 feet per mile. Thus, the profile of a pediment is gently concave upward. Small alluvial fans and talus cones at the mountain front as well as sheets of fluvial gravel are transitory features. Fluvial gravels have commonly been described in connection with pediments, yet gravels do not need to be present. The type of rocks being eroded will determine the texture of the erosion products.

Howard (1942) reserved the term pediment for the portion of the surface that is cut in bedrock and proposed the term peripediment for the erosion surface over skirting alluvium. He combines the two under the term pediplane.

The relationship of pediment and peripediment during development of the pediplane is illustrated in Figure 3 under three conditions: when the base level (A) is constant, (B) is being lowered, and (C) is being raised. Cross section A shows a pediplane forming as a slope of a tributary to a master stream, the base level. In this section alluvium is shown in the downslope area, but after its deposition the master stream has remained at a constant level and pediment cutting in the tributary continued. With the continued retreat of the mountain front the pediment is lengthened, its declivity is gradually lowered, and the peripediment once formed remains practically unchanged. The development of extensive peripediments is rare under the condition of a constant base level.

A rejuvenated master stream incurs active erosion over the entire pediplane and only ephemeral deposits will be formed (Fig. 3B). Under such a situation a new pediment surface would develop to the lower base level and work its way headward. Sediments resulting from the process would be largely removed by the master stream, and peripediment development would remain subordinate.

Pediments may form as alluviation of the valley floor occurs, and the condition is one of a rising base level (Fig. 3C). The surface slopes are markedly flattened due to headward extension of the pediment and building up at the base level. Due to headward erosion of the pediment and aggradation at the base level, the peripediment encroaches and increases conspicuously in area. The cut surface preserved beneath the alluvium has a profile which is convex upward—the opposite curvature from the profile of a pediment. This buried surface has been called the suballuvial bench by Lawson (1915). In regions of rising base level the pediplane will be made up for the most part of a peripediment, and the pediment as a near-mountain zone cut on solid rock is sometimes overlooked.

SPECIAL FEATURES OF PEDIMENTS IN THE VALLEY OF THE LITTLE COLORADO RIVER

Pediments on inclined strata.—The general strike of the beds parallels the course of the Little Colorado River. The beds on the west side dip toward the river, and

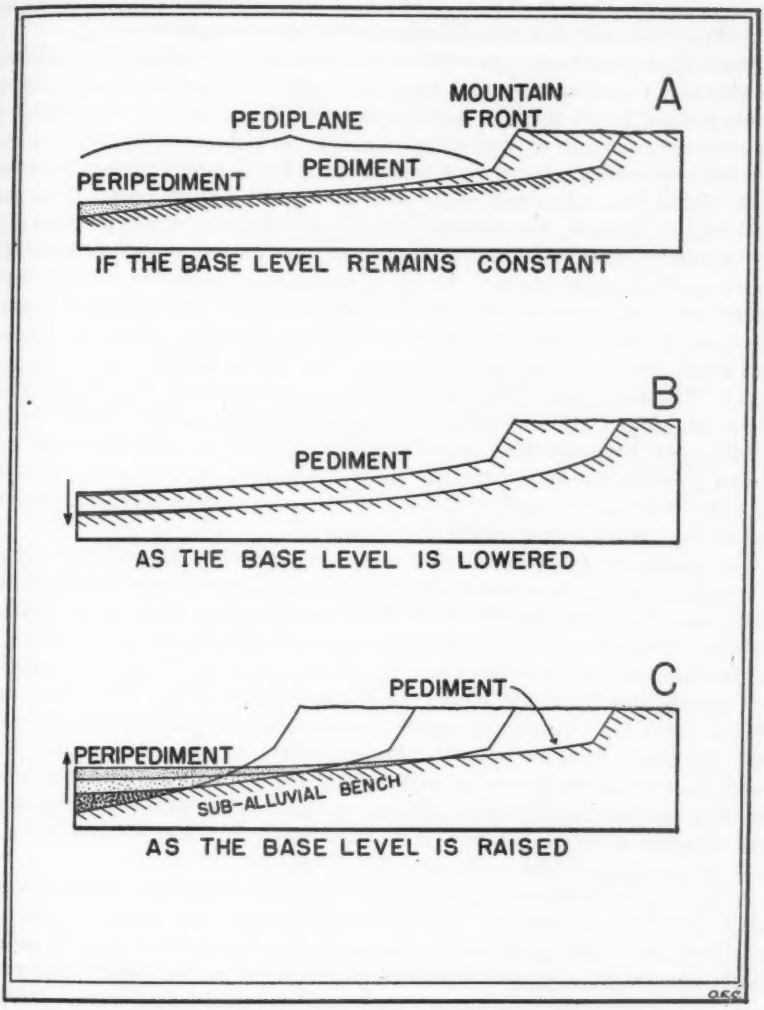

FIGURE 3.—*Relation of pediment to peripediment*

those on the east side dip away from the river. Further, the beds on the west side are largely the resistant sandstones of the Moenkopi formation and the sandstones and limestones of the Kaibab formation, whereas the layers to the east are mainly the soft shales and marls of the Chinle formation. Hence, the pediments grew westward slowly over resistant materials and rapidly to the east over easily eroded beds. Here, then, is an excellent opportunity to observe and describe the sequence

of forms in an arid cycle of erosion that occur over sedimentary beds of different attitude and of beds that offer differential resistance to erosion.

Strata dipping gently upstream.—To facilitate explanation consider first a pediment growing back from a constant base level into a region of sedimentary rocks that are gently inclined in the opposite direction to stream flow (Fig. 4). One stratum is represented as resistant to erosion, and the others as yielding readily. The mountain front retreats by parallel slope recession, and the pediment surface is progressively altered from early, short, steep slopes to late, long, gentle ones. If the base level remains constant, as is assumed, the regional relief may remain the same until the highlands are destroyed, and the sequence of surface features will be essentially bound up with profile changes. As the retreating front passes the resistant layer, the smooth profile is interrupted (Fig. 4, Blocks I and II). The resistant formation serves as an effective base level for stream activity above it. The master stream into which run the smaller streams is base level for drainage below the resistant strata. The knickpoint caused by the resistant beds gradually lowers and moves headward. Down the slope from the knickpoint pedimentation rapidly reaches stability, but headward the constant regrading of slopes to a changing base level results in widespread dissection with limited pediments extending back from the streams. Eventually the knickpoint is lowered until the profile is continuous across the resistant strata (Fig. 4, profile C and block III).

The interfluvial areas are retarded in development (Fig. 4, profile A). Below the resistant bed, as the mountain front retreats, a pediment forms to the base level and heads against the resistant layer which forms the front of a cuesta. Upslope from the cuesta the surface is drained by gullies that reach headward from the front of the cuesta or that flow into the main tributary streams. Gradation is slow in this retarded headland, and playas may be impounded locally behind the cuesta (Fig. 4, b'ock II). Finally, dissection progresses into the region either by retreat from the cuesta front or laterally from the valleys of accelerated erosion. The cuestas are by-passed by the general surface, and the retarded interfluve profile becomes continuous with main tributary profiles. Thus profile C becomes the general profile of the pediment to its constant base level. Remnants of the cuesta may still be present and would be called inselbergs.

If the beds are horizontal, retarded headlands with playas and local back slopes would probably not develop. Pediments upslope from the resistant escarpment would be temporarily graded to the knickpoints of the headward-growing notches in the escarpment, later to be dissected and regraded as the lower surface grows into the highland along major stream channels. Eventually here, too, a profile will develop to the controlling constant base level comparable to profile C.

Strata dipping gently downstream.—In regions where sedimentary beds dip in the same direction as the streams flow, the details of surface forms will appear about as shown on Figure 5. When the retreat of the mountain front lays bare the resistant stratum the profile of fastest erosion will be along the main stream channels (Fig. 5, profile B). Downstream from the resistant zone the pediment will be controlled by the constant regional base level (here the Little Colorado River) and will head against the resistant layer. A strip-plane will form first over the resistant bed and

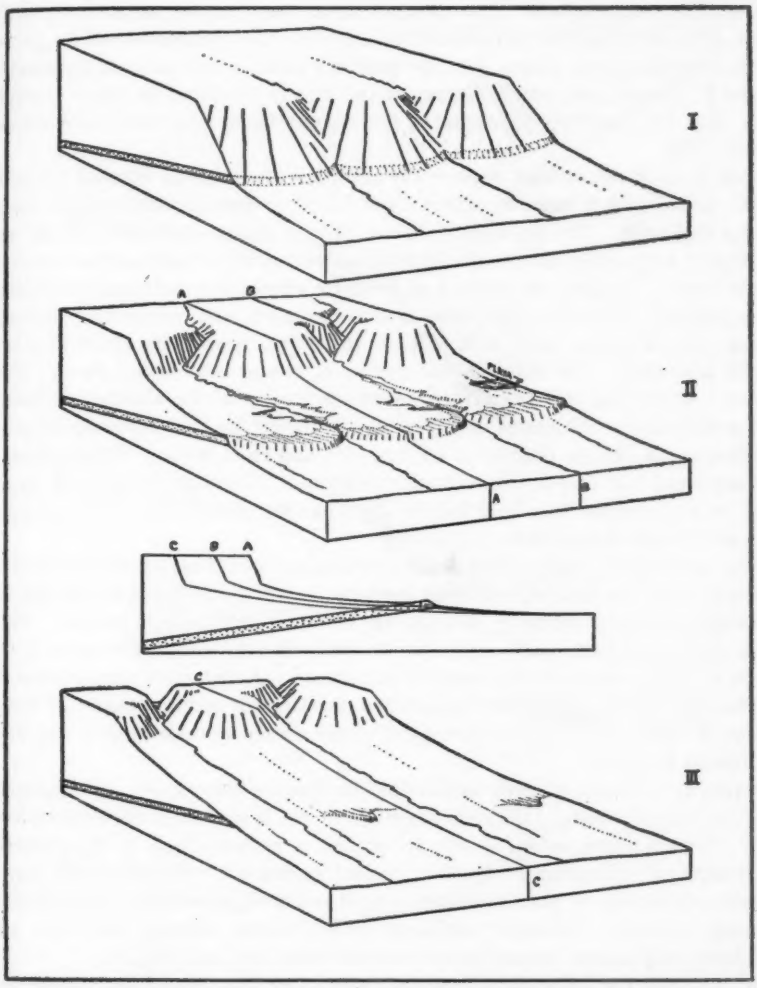

FIGURE 4.—*Profile development with beds dipping gently upstream*

then a narrow canyon along the stream. A series of knickpoints will form in "rapids" fashion, if the resistant member is made up of a number of beds of considerable thickness, and in working headward will cut through the resistant stratum. Upstream from the resistant zone small pediments will form and will be dissected as each knickpoint migrates headward. Finally, a profile controlled by the regional base level will develop. Interfluvial areas will again be the site of retarded erosion (profile A). Downslope pediments will form to the constant base level and head

against the resistant beds. The resistant strata may become an extensive strip slope, only locally gullied and scoured, and the headland pediments will be graded to the extensive strip slopes. As the general surface is lowered and approaches Profile C, the resistant zone is by-passed and mostly truncated by many drainage lines, and low inselberg remnants of the cuestas facing upstream may remain (block III).

Cycle of erosion in inclined strata.—The arid cycle of erosion as reported by Davis (1905) begins with a series of valleys down-folded or down-faulted between intervening highlands. The sequence of forms through youth, maturity, and old age takes place with a rising base level due to an alluviation of the basins as the mountain fronts recede. To keep the features of the cycle simple, the rocks were considered homogeneous. Through youth, relief is at a maximum, and independent drainage basins with local base levels exist. Relief is reduced in maturity and divides are locally destroyed as the drainage and profiles of two or more basins become integrated. With continued lateral and headward growth of the alluvial piedmonts and pediplanes the mountains that once stood between the basins become irregular inselbergs. In old age pediplanes are extensive and relief is low. Highland areas are destroyed, and only scattered inselbergs remain. Drainage of an entire region may have a common base level and for the most part profiles are very near equilibrium or ultimate gradation.

The changes from independent drainage basins and local base levels to integrated drainage and a common regional base level are the principal criteria for designating the stages of youth, maturity, and old age in Davis' arid cycle of erosion. Since these features are not clearly applicable to the erosional forms in the region of the Little Colorado other criteria must be summoned. A deductive consideration of the form of profiles through the sequence of development makes possible the designation of cyclic stages, which correspond rather closely to those already described in Figures 4 and 5.

Youth is the stage wherein longitudinal profiles are interrupted, and migrating knickpoints are present. Only the lowest pediment is graded to the regional base level. Others higher on the profile are graded to resistant beds in the drainage. Pediments are characterized by their limited extent and relatively steep slopes. Headward extension of planed surfaces is rapid and most pronounced along principal drainage channels. Retarded headlands behind cuestas, zones of dissection, and extensive strip planes abound where resistant beds crop out (Fig. 6).

In maturity the knickpoints have been destroyed, and longitudinal profiles are continuous. The pediment surface has by-passed resistant zones leaving subdued remnants of cuestas in the interfluvial areas. The pediments have merged laterally to form extensive planed surfaces. The zone of most active erosion is immediately in front of the retreating mountain front where the steepest part of the profile exists. The entire mature profile is dominated by the regional base level.

In old age the extensive pediplanes are lowered until they have approached the ultimate profile of gradation. Steep slopes of active erosion are absent, and highland areas have been destroyed (Fig. 6). Thus, the relief of youth and maturity is lost.

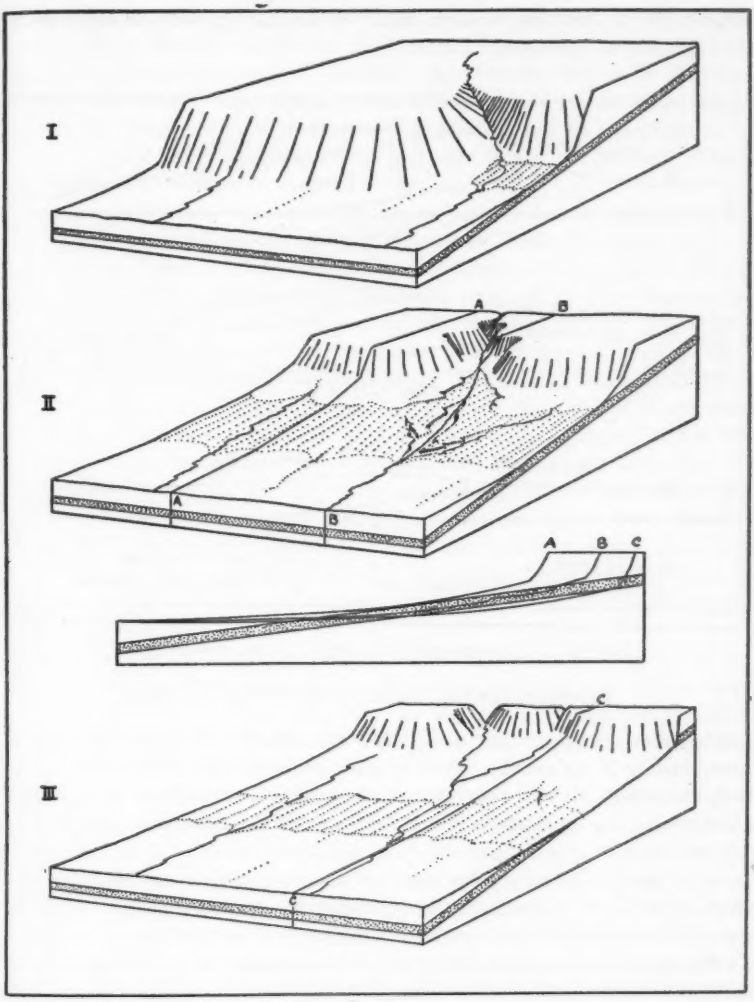

FIGURE 5.—*Profile development with beds dipping gently downstream*

The general declivity of the surface will be near the profile of equilibrium which is controlled by climatic conditions and gradient.

If the master base level is lowered, an epicycle will be imposed on the above sequence of events. Dissection and limited local pedimentation will ensue until the regional base level is stabilized after which the new pediments will expand, adjusted to the lower base level. The base level is the most important control during a cycle

of erosion, for its behavior, whether stable or fluctuating, must be reflected in the surface features of the region affected by it.

FIGURE 6.—*Pediment cycle of erosion in a region of inclined beds*

PEDIPLANES IN THE VALLEY OF THE LITTLE COLORADO

General characteristics.—The pediplanes adjacent to the Little Colorado River consist mainly of pediments. Only limited peripediments exist as gravel-capped interfluvial tablelands near the river. The gravel fills, over which the peripediments have formed, are in most places from 4 to 8 feet thick and consist mainly of rounded chert pebbles. In general, gravels on the pediments are not thicker than the depth of scour of floods. In a very few places, however, gravel fill reaches a thickness of 25 feet. The Little Colorado River apparently has been able to carry away readily most of the sediments that have been brought to it from its flanking pediments.

In the region of this study three principal pediplane surfaces are suggested. Projection of the surfaces from either side of the Little Colorado River Valley to a line of intersection indicates that the regional base level has lowered and become stable at least three times. Each time stability of base level has endured for a shorter and shorter time. In each of the three positions the Little Colorado River as the master stream has followed a course nearly directly below its previous course. The lowest surface is now being developed to the present position of the Little Colorado River and to the large, tributary Tusayan Washes that enter from the northeast (Fig. 1). This surface will be called the Little Colorado pediplane. In the Wupatki area remnants of an intermediate surface are approximately 200 feet above the river. These pediment remnants stand as truncated interfluvial table lands between the

abrupt arroyos that drain the area. The surface represented by the remnants will be called the Wupatki pediplane. A remnant of a surface 600 feet above the Little Colorado River is preserved beneath a thin basaltic flow at Black Point, 9 miles north of Wupatki National Monument. Other high remnants occur elsewhere, and the surface indicated by them is referred to as the Black Point pediplane.

Plate 4 presents the general distribution and character of the pediment remnants and other erosional features in the area studied.

Black Point pediplane.—The Black Point pediplane is named from Black Point about 9 miles north of Wupatki where it is preserved beneath basaltic lava. The surface over which the lava flowed is a pediment sloping approximately 20 feet to the mile toward the Little Colorado River and heading against the San Francisco highland to the southwest. It was developed for the main part over the red sandstones and shales of the Moenkopi formation which are inclined in the same general direction and about the same amount as the pediment. The surface passes uninterrupted over the Black Point monocline and truncates the beds that are bent down sharply. The relation of pediment surface to the structure of the underlying beds is shown clearly here where the pediment has been protected beneath the lava cover while adjacent areas have been lowered by subsequent erosion. Northwest of Black Point (Pl. 4) the destruction of the Black Point surface has begun. Here the surface is represented by flat-topped interfluves on the Moenkopi formation. Lava bounds this area of the old surface on three sides and has retarded destruction by the streams that drain this section. Thus, it is believed that dissection of the pediment has gone on very slowly here.

Farther northwest, downstream on the Little Colorado, remnants of the Black Point pediplane have been destroyed in the deeply dissected and widely stripped area of the Marble Platform (Fig. 1). As the gorge of the Little Colorado deepens, toward its junction with the Colorado River, the general surface of the region rises steadily toward the Coconino and Kaibab plateaus. This surface of the Marble Platform is a vast stripped and dissected plane on the Kaibab formation rising well above the Black Point pediplane. It is assumed, therefore, that the Little Colorado River was flowing in a deep canyon across most of the Marble Platform when the Black Point surface was forming in the upstream regions.

Southward from Black Point, over White Mesa and Antelope Prairie, the pediment surface has also been destroyed. Stripping down to the resistant Kaibab limestone has occurred, and the Kaibab in turn has been dissected by the tributaries of the Little Colorado. The dissection is less pronounced westward over the nearly flat plain of White Mesa. The deep entrenchment at the front of the monocline has not cut far headward except along large tributaries. On to the south, from Woodhouse Mesa to Merriam Crater (Pl. 1), Stage 1 lava flows can be traced almost without a break. They emerge from beneath the younger flows and are seen on a continuous surface cut over Moenkopi sandstone and shale. This surface is clearly a continuation of the Black Point pediplane.

Southwest of the area mapped the Kaibab formation rises steadily toward the summit of the San Francisco Plateau. Here Highway 66 ascends a gradual slope which suggests an extensive surface stripped to the resistant Kaibab. However,

the dip of the beds does not everywhere coincide with the surface. Local swells and sags in the structure are truncated. At the contact with the softer Moenkopi the surface is preserved as flat-topped obsequent cuestas in the contact zone. The position and elevation of this erosion surface suggests that it is a continuation of the Black Point pediplane and was preserved because it was developed on resistant beds. Subsequent erosion has only locally dissected and stripped it, as at Canyon Diablo, Canyon of the Padre, and at Walnut Canyon.

East of the Little Colorado opposite Black Point, shales and weak sandstones predominate, and the Black Point pediment has been preserved only on the most resistant rocks. A resistant bed near the top of the Chinle formation forms the crest of a long somewhat irregular cuesta that faces the Little Colorado River. At several places this cuesta has been breached, and at other places it forms the "mountain front" for pediments of the present valley floor, but its flattened, gravel-capped crest stands as a narrow remnant of the older and higher Black Point surface (Pl. 4, profile A′–A). Farther east the crests of the Wingate and Navajo cliffs are pediment remnants of the Black Point pediplane. North of Dinnebito Wash, a narrow peripediment remnant of the Black Point surface forms the divide between the drainage to Dinnebito Wash and to the Little Colorado River (Pl. 4, profile B–A).

The surface of this remnant is continuous with that of the crest of the cuesta and is developed over gravels which reach an unusual thickness of 25 feet. The length of the ridge is approximately 5 miles, and it is extremely narrow throughout. Extensive gullying along the flanks emphasizes attack by vigorous erosion. Possibly the thick gravel capping may be in part responsible for the local preservation.

The preservation of the peripediment remnant north of Dinnebito Wash is fortunate because the slope of the Black Point surface east of the Little Colorado can be determined by means of it. The declivity of the surface is much the same as that beneath the lavas of Black Point, and projection of the two surfaces shows that the master stream of the region was approximately 600 feet above the present course of the Little Colorado River.

Robinson (1907) reported the erosion surface under the lava flow at Black Point as a local remnant of a widespread "peneplain" covering thousands of square miles in the Plateau country. In a later report (1913) he believed the surface to be the product of Dutton's "Great Denudation" following the first period of faulting at the close of the Miocene. During the faulting the large elements of the plateau province were outlined, according to Robinson, much as at present. He dated his "First period of volcanic activity" in the San Francisco Peaks area as Late Pliocene because the lavas had poured out upon the extensive surface that resulted from the "Great Denudation", or "peneplain cycle of erosion", which, he assumed, required most of the Pliocene epoch.

In the immediate vicinity of Black Point there seems to be little information about the age of the Black Point pediplane except that it is older than the Stage 1 lavas. Robinson's dating had no stratigraphic or fossil foundation, and, therefore, it becomes necessary to seek other evidence for age determination.

North of the Little Colorado River upstream from Leupp is a region of Tertiary volcanic and sedimentary rocks known as the Hopi Buttes (Fig. 1). Various aspects

of this area have been reported by Gregory (1917), Williams (1936), and Hack (1942). Williams (1936) recognized that the lavas and lacustrine sediments of the Hopi Buttes accumulated on an erosion surface of low relief. Vertebrate fossils from the sediments include fish, birds, amphibians, beaver, and camels and indicate an age of Middle and Late Pliocene. These beds are included in the Bidahochi formation of Hack (1942). The formation reaches a thickness of 400 feet and is made up of water-laid marl, calcareous tuff, clay, and sand.

A traverse from the Little Colorado River at Winslow northward into the Hopi Buttes shows a series of pediment levels much the same as those in the regions downstream near Wupatki and Black Point. At Winslow the river is at an elevation of approximately 4850 feet, and to the north the surface rises steadily. The first 250-foot rise is over an irregular gullied surface of dissection and rolling sand dunes beyond the surface that is evidently the Little Colorado pediment. Then for 7 miles the ascent is over the general surface of a pediment mantled with 4 to 6 feet of gravel and rising with a general slope of 20 feet to the mile. This erosion surface from all characteristics is the same as the Wupatki pediplane downstream. It heads against a resistant horizon near the top of the Chinle formation, and 200 feet higher a pediment surface (600 feet above the Little Colorado River) continues on into the Hopi Buttes. This highest pediment is believed to be a part of the Black Point pediplane and as a general surface rises to each of the local buttes which stand above it as inselbergs. The Black Point pediplane heads far back in the mesa and plateau elements of the region and truncates the Bidahotchi formation in many places, as, for example, at Castle Butte where the elevation is 5450 feet. Thus, the Black Point pediplane is more recent than the Pliocene lavas and sediments of the Hopi Buttes and is probably latest Pliocene or early Pleistocene.

The "Hopi Buttes Peneplain" of Gregory (1917), referred to by Hack (1942), is the surface on which the lavas and sediments accumulated. During the development of the Black Point pediplane the lava-capped areas of the Hopi Buttes Peneplain formed a highland into which pediments grew from the Little Colorado River. The Black Point surface reaches lower and is younger than Gregory's "Hopi Buttes Peneplain" and cannot be correlated with it as suggested by both Gregory (1917) and Hack (1942). Since the Stage 1 lavas of the San Franciso field spread over parts of the Black Point pediplane which is younger than the surface beneath the Hopi Buttes lavas, the San Francisco lavas are clearly more recent than those of the Hopi Buttes.

The Wupatki pediplane.—Immediately south of Black Point and along the northern margin of the Wupatki Basin there are numerous remnants of a pediplane surface 150 feet above the river. This surface is the Wupatki pediplane (Pl. 4, profile A′–A). To the west it heads against Moenkopi beds, which are upturned sharply in the Black Point monocline, and is developed over Moenkopi and Shinarump beds. The surface here is a pediment with only a thin mantle of gravel, and it slopes toward the Little Colorado River with a gradient of approximately 30 feet per mile. The beds are inclined eastward slightly more than is the surface, and they are therefore truncated. Near the head of the pediment the beds are locally wrinkled into a small syncline and anticline, both of which are truncated by the surface. Across the river, along

the line of cross section A′–A in Plate 4, the Wupatki pediplane rises to the distant Chinle cliffs. The declivity of the surface is comparable with that west of the river. Near the river the surface is locally a peripediment over gravel that reaches a maximum thickness of 20 feet. This remnant is now an inselberg by-passed on both sides by a still lower surface.

Along the southern margin of the Wupatki basin the Wupatki pediplane is preserved beneath basaltic lavas of Stages 2 and 3 (Pl. 1). Here the surface is comparable in slope and elevation with that beneath Black Point and is a pediment developed on Moenkopi beds.

The river crosses the Tolchaco anticline in a canyon zone from Tolchaco to Black Falls. Along this zone the Wupatki pediment approaches the top of the canyon walls from both sides. West of the river the surface heads against the highland of the Black Point surface capped with lava. The Wupatki pediment is well preserved here, giving way to deep dissection only near the river. Much of the Wupatki surface west of the river is covered by lavas ranging in age from Stage 2 to Stage 4.

East of the river many interfluvial areas are remnants of the Wupatki surface, but dissection is fairly advanced. In the canyon zone of the Little Colorado the Dinnebito Wash enters as one of the largest tributaries. This tributary was well established before the Wupatki pediplane had been eroded because the Wupatki surface extends along the flank of the long Black Point pediplane remnant north of Dinnebito Wash (Pl. 4). Here the pediment slopes toward the wash rather than toward the Little Colorado, and indications are that during this stage a surface, tributary to the Wupatki of the Little Colorado, developed far up Dinnebito Wash. Further, the Wupatki remnant along the north side of Dinnebito emphasizes the concept that the Wupatki pediplane was a youthful surface with interrupted profiles. It reached beyond the cuesta of the Chinle Cliffs and developed a retarded headland between the cuesta and the Wingate cliffs. Still, the Wupatki pediplane was far enough advanced to have extended widely over the resistant Moenkopi beds west of the river.

West of Leupp the Wupatki pediplane was formed over Moenkopi beds, and it heads against the resistant Kaibab over on the Tolchaco anticline. The major tributary to the Little Colorado in this area is made up by the merging of Walnut Creek, Padre Creek, and Diablo Creek. The latter two flow in gorges 150 feet deep through the anticline and merge near the axis of the fold (Pl. 1). They seem not to have been deflected by the anticline that stands across their paths, and, therefore, these courses were developed on a higher and older surface than the Wupatki.

North of Leupp the road to the Hopi Villages ascends a long remnant of the Wupatki surface. In the northwest cross section this spur is distinctly asymmetrical. Its northwestern flank is abrupt and drains to the Little Colorado River. To the southeast the slope is gentle as the spur forms the head of a pediment grown back from the present position of Polacca Wash (Pl. 4). The top of the spur is flattened and capped with gravel. The gravel veneer thins from 15 feet to 2½ feet upslope. This Wupatki pediplane remnant is 4½ miles long. Toward the head the slope is 50 feet per mile, and it flattens downslope to 20 feet per mile.

It is possible to make more projections of profiles of the Wupatki pediplane and to restore the surface more completely than the Black Point. The slope of the remnants of the Wupatki surface would require a master stream 70 feet above the Little Colorado at Leupp, and 150 feet above the river at Black Point. This would produce an average gradient for the base-level stream of 10 feet per mile, and the early channel would be approximately along the same course as the present Little Colorado.

The Wupatki surface was developed in the erosion interval between the lava flows of Stage 1 and Stage 2. It is older than the acidic volcanic rocks of the San Francisco Peaks (Table 1), which were later subjected to glaciation. Hence, the Wupatki pediplane is earlier than the first glacial stage in the San Francisco Mountains and is probably early or middle Pleistocene.

The Wupatki "B" pediment.—The Indian ruins of Wupatki National Monument stand on a remnant of a pediment which accords in level with other flat-topped interfluvial remnants in the Wupatki basin (Pl. 3, fig. 2). The surface represented by these remnants heads against the monocline and against the lava-capped Woodhouse Mesa. At its head it is slightly lower than the Wupatki pediplane beneath Black Point. The slope of the lower surface toward the Little Colorado River is more inclined, and the remnants of the surface are only 75 feet above the river. This pediment will be called the Wupatki "B" pediplane (Pl. 4, Sec. B–A). It was observed well developed only in the Wupatki basin, but suggestions of it appear west of the river between Black Point and Cameron. East of the river the rapid development of the still lower Little Colorado pediment has left no certain remnants of it. In age it is clearly intermediate between the Wupatki surface and the Little Colorado surface. However, the Wupatki "B" pediment may correlate with a part of the Little Colorado pediplane where the latter is developed upstream from the canyon zone in the region of Leupp.

The Wupatki "B" surface is in such a position as to suggest that it, together with the Little Colorado surface upstream from the canyon zone, represents the first period of stability in the profile of the Little Colorado River after entrenchment of the Wupatki pediplane began. The surfaces could not have been continuous but would have been separated by a canyon zone nearly as long but not so deep as the present one. Subsequent lowering of the profile to the present level downstream from the canyon zone would have occurred while knickpoints were migrating upstream and were deepening the canyon zone. The Little Colorado pediments upstream from the canyon zone would thus become a retarded headland for the stream activity in the Wupatki basin. The Wupatki "B" pediment owes its existence to actively eroding tributaries flowing from the San Francisco highlands, and these tributaries, if influenced by a short period of stability in the position of the master stream, would have carved the Wupatki "B" surface.

Little Colorado pediplane.—The Little Colorado pediplane is the surface now developing to the present position of the Little Colorado River. It is an extremely youthful pediplane and has extended only into readily eroded materials. The absence of dissection makes it difficult to determine the extent of peripediment development, but a pediment surface probably predominates. The Little Colorado surface can best be described in three sections along the river: (1) the region up-

stream from Cameron to the canyon zone south of Black Falls, (2) the canyon zone from south of Black Falls to a point 16 miles upstream where the valley opens out again at Tolchaco, and (3) from the head of the canyon zone upstream to Leupp and the Polacca Wash tributary (Pl. 4).

At Cameron the Little Colorado River enters the narrow gorge in which it continues to its junction with the Colorado River in the Grand Canyon. Yet, upstream from Cameron the river flows along the western side of a broad open valley with gentle pediment slopes rising eastward to the cuesta of the Chinle Cliffs. Although the region to the west is deeply dissected the resistance of the Moenkopi and Shinarump beds has so inhibited pediment growth that only limited pediment embayments have extended up tributary streams. To the east an extensive pediment surface has developed over the soft lower Chinle beds and heads against the cuesta formed by the resistant upper beds of the formation. Along some of the larger tributary streams the surface steepens abruptly and reaches beyond the cuesta front into the retarded headland. The general youthful picture of limited pediment development into regions of resistant rock and extensive growth into the soft beds of the Chinle formation characterizes this entire section. In the southern part of the section, *i.e.*, from Black Point to the canyon zone south of Black Falls, the Little Colorado pediplane has by-passed and isolated inselberg cuestas of Moenkopi and Shinarump rocks. The summits of the inselberg cuestas are remnants of the Wupatki pediplane (Pl. 4).

The river passes through a 16-mile canyon zone that extends from Tolchaco nearly to Black Falls. This is a zone of vertical dissection through the resistant beds of the Kaibab formation, and lateral pediment development has not begun. Upstream from Grand Falls the narrow canyon has been filled with alluvium behind the lava dam of Stage 4 lavas (Pl. 1; Pl. 2, fig. 2). Over the top of this alluvial fill the river has found its way around the end of the lava dam and now plunges 175 feet back into its own gorge (Pl. 2, fig. 1).

Dinnebito Wash debouches through a narrow gorge into the Little Colorado in the canyon section. Upstream, Dinnebito Wash is on the soft beds of the Chinle formation, and an extensive pediment surface has grown. It has the appearance of a tributary surface to the general Little Colorado pediplane.

In the region from the canyon zone to Leupp the pediment surface has grown back from the river, again mainly to the east. The youthfulness of the Little Colorado pediplane is realized when it is noted that upstream from the canyon zone the pediment is graded to its master stream at an elevation of 380 feet above the same surface downstream, opposite Black Point. The upstream region can be regarded as a retarded headland along the master stream, held back in development by the existence of knickpoints in the canyon zone along the longitudinal profile of the Little Colorado River. Due to a lowered base level, the pediplane in the upstream area probably would now have been widely affected by dissection if the migration of the knickpoint had not been checked. The headward migration of knickpoints through the canyon zone has been interrupted by the lava dam of Grand Falls and deep sediment fill behind it.

Polacca Wash enters the river at Leupp, and the general pediplane to the master stream merges with that of the tributary.

The obvious recent geologic age of the Little Colorado pediplane emphasizes the recency of Stage 3 and Stage 4 lavas which are on it. Lavas of both stages have followed down channels that are headward extensions of streams flowing over the youngest pediment. Pedimentation and dissection had advanced to a stage wherein the topography was comparable with the present before Stage 3 lavas were extruded. From glacial studies in the San Francisco Mountains, Sharp (1942) concludes that Stage 3 lavas are post-Iowan-Wisconsin.

LITTLE COLORADO VALLEY AND THE GRAND CANYON

Concepts of Grand Canyon morphology.—The sequence of events in the cutting of Grand Canyon has long been the concern of many investigators in the plateau region. In the first approach to the problem Powell (1875, p. 198) states that, "... the system of drainage was determined antecedent to folding and faulting." He envisioned a long period of prodigious erosion as the region was slowly raised against the Colorado River and its tributaries. Dutton (1882), agreeing with the concept of antecedency, described an interrupted uplift of the region resulting in two great cycles of erosion. "The Great Denudation", he postulated, was started by early Tertiary uplift and continued until Pliocene time when renewed uplift resulted in the "Canyon cycle" of erosion. This has been in progress to the present. Davis (1901) followed Dutton in the concept of two cycles of erosion; he contended that the Colorado River was not antecedent to the structures but was in part a consequent stream determined in its initial position by the slopes of an ancient depositional surface. The depositional surface resulted from the accumulation of Tertiary sediments following the Laramide revolution. He used the term "plateau cycle" in place of the great denudation.

The great denudation was supposed to have resulted in a peneplain, and vigorous erosion in the highlands has since destroyed most of it. However, several surface remnants were noted in the Plateau country and ascribed to the general "peneplain." The surface beneath the lavas of Mt. Trumbull on the Uninkaret Plateau was pointed out by Dutton (1882), and later by Davis (1901). The surface beneath the lavas at Black Point was described by Robinson (1907). The "Hopi Buttes peneplain" beneath lava was reported by Gregory (1917). All were considered local remnants of the regional peneplain of the great denudation.

Based on the previous regional studies Gregory (1933) presented the current concept of the geomorphic history of the Colorado Plateau country. His sequence of events may be summarized as follows:

(1) After widespread deposition of the Eocene strata regional uplift occurred, and consequent drainage developed on the slopes and inequalities of the uplifted block. The larger streams cut through the Eocene strata and became superposed on the Laramide structures.

(2) In the erosion that followed (Dutton's "Great Denudation" and Davis'

"Plateau Cycle") Cenozoic and Mesozoic beds were removed. Quoting from Gregory,

> "Parts of the present surface of the Kaibab, Kanab, Uinkaret, Shivwits, and Coconino plateaus are thought of as remnants of the plain formed at the end of this first period of erosion."

(3) Regional uplift of 6000 to 8000 feet, probably not all at one time, introduced the "Canyon cycle" of erosion. Erosion has continued to the present.

The erosion surfaces of the Little Colorado as interpreted in the foregoing pages add considerably to the currently accepted theory of the origin of the Grand Canyon; the following pages will be devoted to a discussion of the relationship.

Grand Canyon related to Little Colorado morphology.—The peneplain character of the earliest surface is immediately troublesome in the light of the modern concept of pediments in arid countries, and even to early investigators the nature of the surface appears in doubt, because the notions of antecedency and superposition are not clearly based on detailed geologic maps or on widespread tracing of erosion surfaces. Davis (1901) and later Johnson (1909) described open valleys on the Kaibab Plateau as mature stream valleys residual from the peneplain of the early cycle of erosion. Mature features are not compatible with an old-age surface of the extent ascribed to the peneplain at the end of the great denudation. Strahler (1944) has explained the same open valleys on the Kaibab plateau as due to processes of solution. On the Uinkaret plateau the "peneplain" remnants pointed out by Dutton, Davis, and Johnson were studied by Koons (1945). He described the surface beneath the lava of Mt. Emma, Mt. Logan, and Mt. Trumbull as being a typical pediment with a declivity reaching 300 feet per mile. A modern approach to the problem is one by Moore (1926). He concluded that the form of canyons in the Colorado Plateaus indicates at least one well-advanced cycle of erosion preceding the present, but did not consider the subdued surface to be a peneplain. He believed that the surface in parts of the Plateau Province at the close of the pre-canyon cycle showed unreduced plateaus that rose 2000 feet within a few miles from main drainage lines. He suggests further that the Colorado River had possibly begun to carve the Grand Canyon prior to the beginning of the "Canyon circle".

Regarding the Black Point pediplane of the Little Colorado, the lava-covered erosion surface was probably not a part of an extensive peneplain as was suggested by Robinson (1907), because, as it is traced toward Grand Canyon, it is lost against the higher stripped and dissected Marble Platform. (*See* Figures 1 and 7.) Also from previous discussion it seems fairly well established that the Black Point pediplane was developed to the Little Colorado upstream from a gorge through the Marble Platform. A comparable situation exists today where the Little Colorado pediments are forming upstream from the gorge of the Little Colorado River, and also where pediments are forming to Dinnebito Wash upstream from its canyon zone (Pl. 4). Hence, at the Black Point stage the Little Colorado was already entrenched in its lower course through the Marble Platform, and the canyon-cutting cycle was well under way in the Grand Canyon. Possibly the Colorado River had accomplished approximately 2000 feet of its excavation of Grand Canyon. (*See* Black Point stage in Figure 7.)

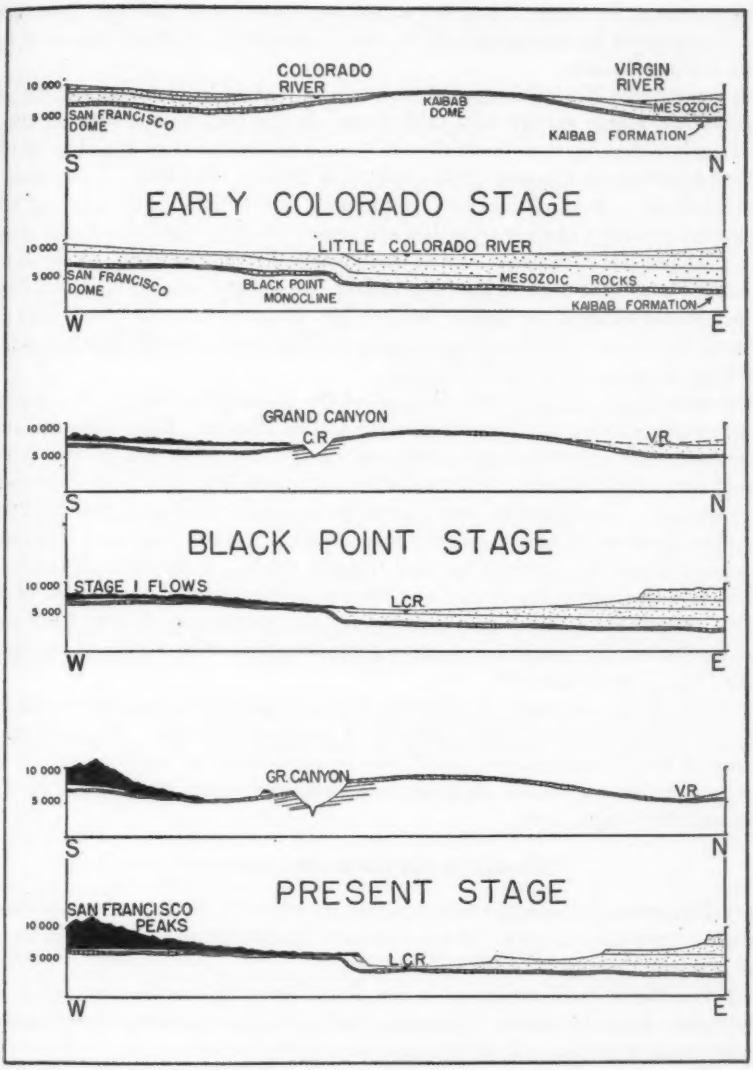

FIGURE 7.—*Relation of Little Colorado morphology to Grand Canyon*

It is particularly significant that the Grand Canyon was already 2000 feet deep when the Black Point surface was formed because there are no higher remnants of pediments in the entire watershed of the Little Colorado, except far to the east in Black Mesa and in the Hopi Buttes.

The course of the Little Colorado was well established prior to Black Point time. This is evidenced in the position of the river indicated by a reconstruction of the Black Point pediplane.

To the east, the Black Point pediplane heads far back in Black Mesa, and features of an earlier, higher surface may exist there. It has been shown that the Black Point surface developed to lower elevations at a later time than the Hopi Buttes surface described by Gregory (1917) and Hack (1942). The Hopi Buttes surface would indicate a period of advanced erosion prior to the Black Point stage and may represent the early Colorado peneplain of Gregory (1917). Later work may prove that other pediplane remnants such as that described by Koons (1945) on top of the Uinkaret Plateau are parts of the early surface that existed prior to the Black Point cycle. Koons believes the surface beneath Mt. Trumbull extended back from the Colorado River at a time when it was flowing near the level of the Kaibab beds which now form the rims of the Grand Canyon.

The sequence of events in the last part of the geomorphic history, the so-called canyon cycle, is indicated in the valley of the Little Colorado. Uplift after the little-understood early Colorado stage caused rejuvenation and dissection, at least in the area of the Little Colorado. After stabilization of base level the Black Point pediplane was cut. The extensive lateral development and mature profiles of the Black Point pediplane would have required a long period of stability, one most reasonably associated with a long interval between regional uplifts. Renewed uplift caused a second rejuvenation of the region, and after a shorter time of stabilization of the Little Colorado River the Wupatki pediplane was completed. A third uplift may have resulted in the youthful erosional adjustments that are occurring in the region today (Fig. 7, last diagram).

The Grand Canyon has been cut through a highland where extensive erosion has removed all but a few scattered evidences of past erosion cycles. The geomorphic history of the Colorado River might best be established by studying further the sequence of events as shown along the major tributaries such as the Paria, the San Juan and the Virgin rivers.

SUMMARY OF THE GEOMORPHIC HISTORY

(1) The geomorphic events evident in the area of the Little Colorado are probably events of "the canyon cycle" of the Colorado Plateau province and make up the final period in the regional geomorphic history.

(2) The Black Point pediplane is the oldest erosional feature observed in the valley of the Little Colorado. However, prior to the development of this pediplane, another erosion surface existed, viz., the Hopi Buttes surface.

(3) The major structural pattern of the region had been established by Black Point time. The major drainage lines of the Little Colorado and the Colorado rivers existed in much the same courses as at present.

(4) The Little Colorado River as a graded stream provided a constant base level from which the Black Point pediplane grew laterally over a wide area and reached an advanced stage of development. This surface spread across sediments of middle or late Pliocene age and is therefore dated as late Pliocene or early Pleistocene.

(5) After the Black Point pediplane had reached an advanced stage of development, Stage 1 basaltic lavas of the San Francisco Peaks volcanic field flowed over part of the erosion surface.

(6) The region was rejuvenated after Stage 1 lavas. The Little Colorado River cut downward, probably as a result of regional uplift, and the Black Point surface was widely dissected.

(7) When the Little Colorado River established a graded profile the Wupatki pediplane developed. The Wupatki surface reached a stage of late youth in which the lower profiles were continuous laterally over resistant Moenkopi and Shinarump beds as well as the easily eroded Chinle formation. In the headland areas east of the river there was local adjustment to resistant beds.

(8) Stage 2 basaltic lavas which antedated the earliest glaciation in the San Francisco Mountains spread over parts of the Wupatki pediplane.

(9) The region was rejuvenated again probably as a result of regional uplift, and the Little Colorado cut downward approximately to its present position.

(10) In downcutting, the Little Colorado has become graded upstream from the resistant Kaibab formation, where knickpoints in the river profile have formed in the canyon zone across the Tolchaco anticline, and at the upper end of the gorge of the Little Colorado near Cameron. The Little Colorado pediplane has formed to the graded segments of the river. Soft beds have been truncated in the headward growth of the pediments while the resistant beds are dissected and show only limited pediment growth.

(11) Stage 3 and Stage 4 lavas have spread over the irregular dissected surface in this last cycle of erosion. Stream channels followed by lavas are nearly modern in their character.

(12) Scarcely more than 1000 years have passed since the volcanic activity of Stage 4. During that time dissection and pedimentation have made few changes.

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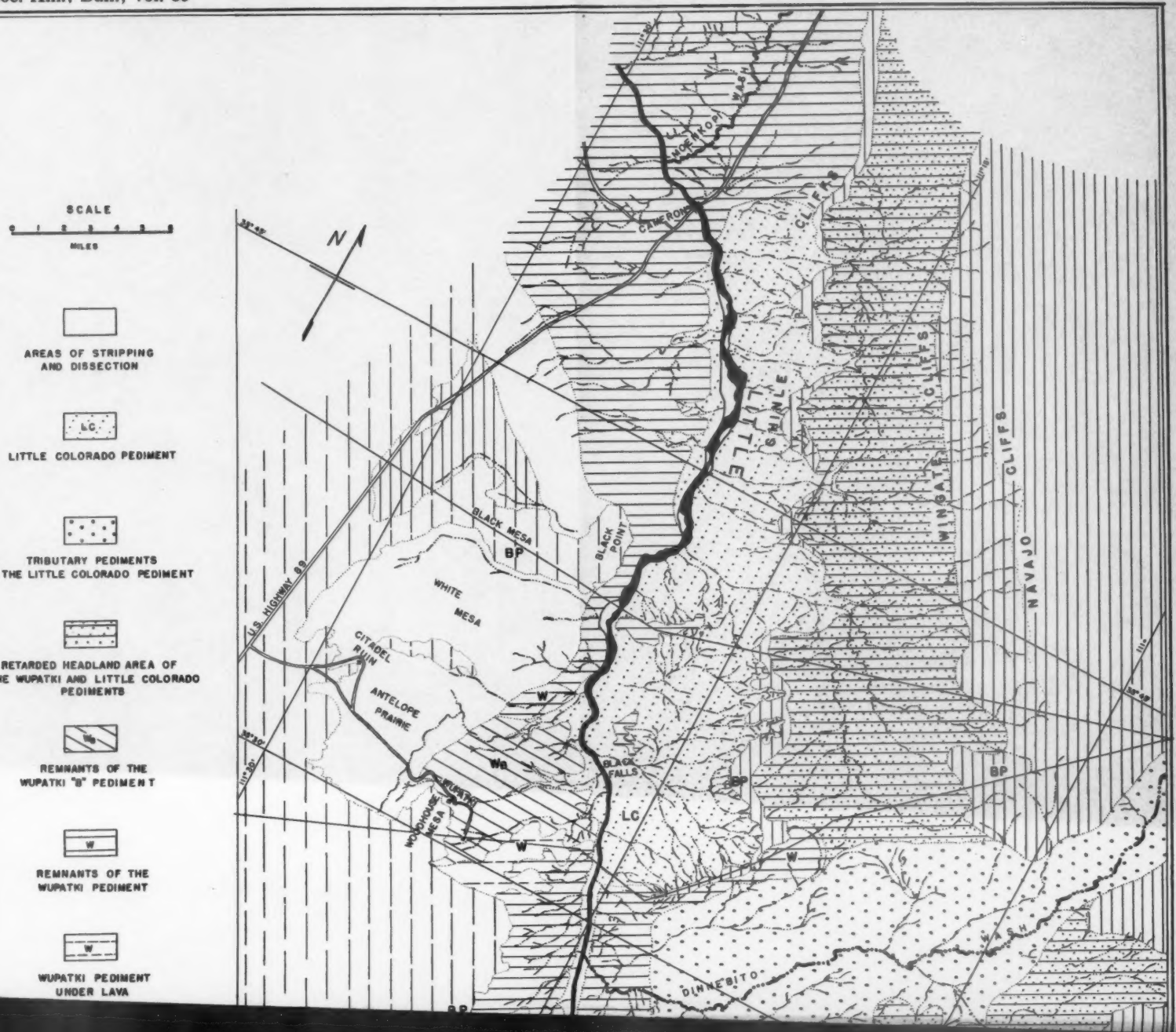
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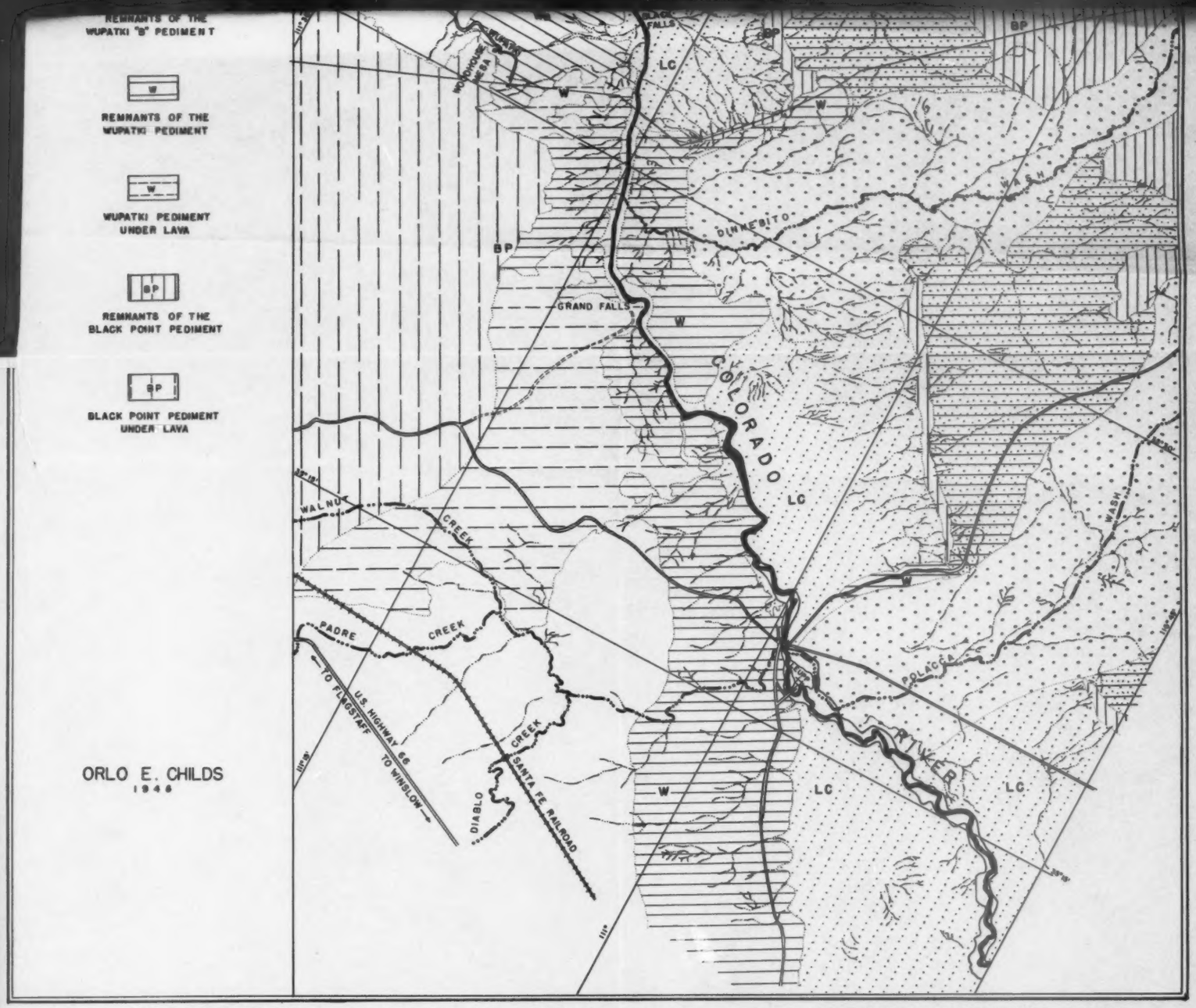
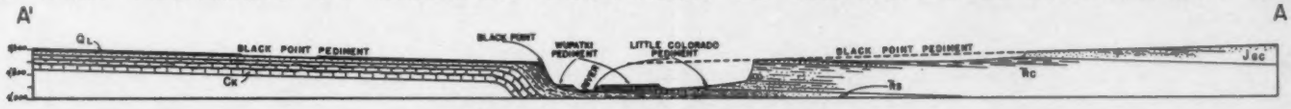
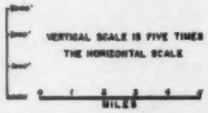
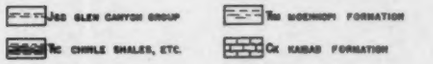


MAP AND SECTIONS OF EROSION SURFACES OF LEUPP-WUPATKI-CAMERON AREA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